

**Human and Environment Interactions in the Environs
of Prehistorical Iron Smelting Places in Silesia, Poland**

—

**Landscape Archaeological and Geoarchaeological Investigations
in the Context of Early Iron Smelting**

Dissertation

zur Erlangung des Doktorgrades
der Naturwissenschaften (Dr. rer. nat.)
am Fachbereich Geowissenschaften
der Freien Universität Berlin

vorgelegt von
Michael Thelemann

Berlin, 2016

First Supervisor

Prof. Dr. Wiebke Bebermeier
Freie Universität Berlin
Institute of Geographical Sciences
Physical Geography
Malteserstraße 74-100
12249 Berlin
Germany

Second Supervisor

Prof. Dr. Brigitta Schütt
Freie Universität Berlin
Institute of Geographical Sciences
Physical Geography
Malteserstraße 74-100
12249 Berlin
Germany

Date of Disputation

May 25, 2016

Acknowledgements

This thesis is financially, technically and scientifically supported by the Cluster of Excellence Exc264 Topoi, which is funded by the German Research Foundation (DFG).

First of all, I would like to address my particular acknowledgements to my first supervisor, Prof. Dr. Wiebke Bebermeier for giving me the great opportunity to participate in this project, for the valuable discussions as well as the intensive support and help. Furthermore, I also would like to address my special thanks to my second supervisor, Prof. Dr. Brigitta Schütt, for her helpful remarks and support throughout the dissertation project. Additionally, I am particularly grateful to our cooperation partners from the Institute of Prehistoric Archaeology of the Freie Universität Berlin, Prof. Dr. Michael Meyer and Dr. Enrico Lehnhardt, for their close, supportive and fruitful collaboration during the selection of the study area, the mutual fieldwork and the work and discussions on our joint publications. I also would like to express my special appreciation to Dr. Michael Prange, Dr. Michael Bode and their colleagues from the German Mining Museum Bochum for their support of the element analyses. Furthermore, I am also very grateful to the anonymous reviewers for their valuable contributions to the publications.

For his assistance and helpful advices during fieldwork and in the laboratory and for his co-authorship in submitted publications, I want to thank Dr. Philipp Hoelzmann. For her support during fieldwork I am especially thankful to Johanna Seidel. Furthermore, I would like to address my appreciation to Dr. Jan Krause for his support in all kinds of administrative issues. I offer my special thanks to my colleagues from the laboratory of the Institute of Geographical Sciences of the Freie Universität Berlin, Frank Kutz, Manuela Scholz and Michaela Scholz for their technical and practical support. Moreover, I wish to acknowledge the support in laboratory work of Elke Heyde and Anna Giribaldi from the Institute of Geological Sciences of the Freie Universität Berlin. I also would like to address my thanks for the practical support to the student assistants René Hahn, Stefanie Bachmeier and Atossa Pandazmapoo as well as to the freelance translator Magdalena Fast. My cordial thanks go to all my colleagues of our working group for the friendly working atmosphere and valuable advices, particularly Jacob Hardt, Torsten Klein, Tina Michel, Martin Schumacher, Julia Meister, Moritz Nykamp, Fabian Becker, Dr. Daniel Knitter and Thusitha Wagalawatta.

Last but not least, I would like to address my very warm thanks to my wife Maria, my family and my friends for their personal support and motivation throughout these years.

Abstract

Within the framework of the interdisciplinary research project (A-5-2) “Iron mining in the Przeworsk Culture” of the Cluster of Excellence Exc264 Topoi, this doctoral thesis deals with the human-environment interactions of early iron smelting in the Widawa catchment area in Lower Silesia, Poland. In this area, which belongs to the southwestern primary distribution area of the Przeworsk culture, a cluster of iron slag sites from the pre-Roman Iron Age and early Roman period is situated. It is assumed that with the emergence of this culture (approximately 2nd century BCE) the technology of iron smelting, originating from the Near East, has been introduced to this area. In order to enable this, respective requirements in terms of the resource situation and landscape conditions needed to be met. Vice versa, deforestation and exploitation of required resources and the smelting activities influenced the landscape development.

This study focuses on three approaches in the context of human and environment interactions in regard to early iron smelting: (i) a resource approach investigating the general resource situation, the favorability for bog iron ores and the geochemical and mineralogical composition of local ores and prehistoric slags; (ii) a landscape approach applying a minimally invasive strategy based on geological and geomorphological mappings, percussion drillings and radiocarbon datings and (iii) an environmental approach focusing on small-scale geochemical impacts of human activities at furnace locations of the prehistoric smelting site of Pielgrzymowice.

Apart from iron ore, considerations on the resource potential implied no scarcity of the required resources during early iron smelting. Distributions of iron contents in receiving waters and presently available bog iron ores indicate a strong correlation with a local cluster of prehistoric slag sites. Slags, collected from these sites, show a similar geochemical composition as slags from other centers of early iron production. In the vicinity of two local sites, Rychnów and Pielgrzymowice, human-induced landscape changes in the temporal context of early iron smelting could be substantiated in alluvial fan respectively slope deposits. On the micro-scale geochemically investigated stove and pile remains at Pielgrzymowice show increased but uncritical heavy metal contents. Human activities in the spatial-temporal context of iron smelting left marks that are even today noticeable in the regional sediment archives. Thus, iron smelting not only had a discernible impact on the human development in general, but also on the landscape in Silesia.

Zusammenfassung

Im Rahmen des interdisziplinären Forschungsprojektes (A-5-2) „Eisengewinnung in der Przeworsk-Kultur“ des Exzellenzcluster Exc264 Topoi beschäftigt sich diese Promotionschrift mit den Mensch-Umwelt-Beziehungen der frühen Eisenverhüttung im Widawa-Einzugsgebiet in Niederschlesien, Polen. In diesem Gebiet, das zum südwestlichen primären Verbreitungsgebiet der Przeworsk-Kultur gehört, befindet sich eine Ansammlung von Eisenschlackefundplätzen der vorrömischen Eisen- und frühen Kaiserzeit. Es wird angenommen, dass mit dem Aufkommen dieser Kultur (ungefähr 2. Jh. v. Chr.) auch die aus dem Nahen Osten stammende Eisenverhüttungstechnologie in diesen Raum eingeführt wurde. Um dies zu ermöglichen mussten entsprechende Anforderungen hinsichtlich Ressourcensituation und landschaftlicher Gegebenheiten erfüllt sein. Umgekehrt haben Entwaldung und Gewinnung notwendiger Ressourcen und Verhüttungsaktivitäten die Landschaftsentwicklung beeinflusst.

Diese Untersuchung folgt drei Ansätzen im Kontext der Mensch-Umwelt-Beziehungen in Bezug zur frühen Eisenverhüttung: (i) einen Ressourcenansatz, der die generelle Ressourcensituation, die Günstigkeit für Raseneisenerze und die geochemische und mineralogische Zusammensetzung lokaler Erze und prähistorischer Schlacken untersucht; (ii) einen Landschaftsansatz mit einer minimalinvasiven Strategie basierend auf geologischen und geomorphologischen Kartierungen, Bohrungen und Radiokarbondatierungen, und (iii) einen Umweltansatz mit Fokus auf kleinräumigen geochemischen Auswirkungen menschlicher Aktivitäten an Ofenstandorten des prähistorischen Verhüttungsplatzes Pielgrzymowice.

Abgesehen von Eisenerz ließen Betrachtungen zum Ressourcenpotential auf keine Knappheit der notwendigen Ressourcen während der frühen Eisenverhüttung schließen. Verteilungen von Eisengehalten in Vorflutern und heute verfügbaren Raseneisenerzen deuten auf eine starke Korrelation mit einer lokalen Ansammlung prähistorischer Schlackefundplätze hin. Von diesen Plätzen gesammelte Schlacken zeigen eine ähnliche geochemische Zusammensetzung wie Schlacken anderer früher Verhüttungszentren. In der Umgebung zwei lokaler Plätze, Rychnów und Pielgrzymowice, konnten menschlich induzierte Landschaftsveränderungen im zeitlichen Kontext der frühen Eisenverhüttung in Schwemmfächer- bzw. Hangsedimenten nachgewiesen werden. Kleinräumig geochemisch untersuchte Ofen- und Meilerreste bei Pielgrzymowice zeigen erhöhte, aber unkritische Schwermetallgehalte. Spuren menschlicher Aktivitäten im zeitlich-räumlichen Eisenverhüttungskontext sind auch heute in den Sedimentarchiven erkennbar. Dementsprechend beeinflusste die Eisenverhüttung nicht nur die generelle menschliche Entwicklung, sondern auch die Landschaft in Schlesien.

I. Contents

1.	Introduction	1
2.	State of the art.....	4
2.1	Theoretical integration.....	4
2.2	Geoarchaeological and archaeometallurgical research on bog iron ores and slags in Central Europe	5
2.3	Research on landscape reconstruction	6
2.4	Early human-environment interactions in Silesia.....	7
2.5	Beginnings of iron smelting in the Przeworsk culture	8
3.	Regional setting and study area	10
3.1	Study area	11
3.2	Geotectonic and geological setting.....	12
3.3	Climate.....	13
3.4	Soils	14
3.5	Vegetation.....	14
3.6	The Widawa River, its hydrology, morphometry and younger history.....	15
4.	Material and methods	18
4.1	General approach	18
4.2	Field work.....	20
4.3	Laboratory analyses	21
4.3.1	Inductively coupled plasma optical emission spectrometry.....	22
4.3.2	Inductively coupled plasma mass spectrometry	23
4.3.3	Portable energy dispersive X-ray fluorescence spectrometry	23
4.3.4	X-ray powder diffraction.....	24
4.3.5	Magnetic susceptibility	25
4.3.6	pH value and electrical conductivity	25
4.3.7	Phosphate content.....	26

4.3.8	Inorganic and organic carbon estimated from loss on ignition LOI550 and LOI900 and measured with Wösthoff Carmograph and LECO Analyzer	26
4.3.9	Particle size analysis with laser diffraction	27
4.3.10	Dating	29
4.4	Secondary and primary data analyses and spatial visualizations	29
5.	Case studies	31
5.1	Case study I: Iron, Humans and Landscape – Insights from a Micro-Region in the Widawa Catchment Area, Silesia	31
5.2	Case study II: Bog iron ore as a resource for prehistoric iron production in Central Europe – A case study of the Widawa catchment area in eastern Silesia, Poland	63
5.3	Case study III: Landscape history since the Saalian Drenhte stadial in the Widawa Catchment Area in Silesia, Poland: A case study on long-term landscape changes .	82
5.4	Case study IV: Geochemical analyses of charcoal piles and rectangular stoves at the Prehistoric Przeworsk iron smelting site Pielgrzymowice in Silesia, Poland ...	118
6.	Concluding remarks.....	135
6.1	The relevance of the environment and landscape setting for early iron smelting ...	135
6.2	Impacts of early iron smelting on the landscape development and environment....	136
6.3	Project synthesis of archaeological and geographical outcomes.....	136
	References	138
	Appendices	149
I.	Appendix A – Dissertation	149
II.	Appendix B – Case study II.....	154
III.	Appendix C – Case study III	161
IV.	Appendix D – Case study IV	171
	Curriculum Vitae.....	174
	Eidesstattliche Erklärung.....	175

II. List of figures

Fig. 1: A: Location of Silesia, Poland; B: Location of the Widawa catchment area and the study area in the region of Silesia.	10
Fig. 2: Widawa catchment area.	11
Fig. 3: Topography of the study area.	12
Fig. 4: Tectonic faults in Paleozoic and Mesozoic deposits in the catchment area of the Widawa.....	13
Fig. 5: Regional climate variance in the region of the study area.	13
Fig. 6: Soil types of the study area.	14
Fig. 7: Potential natural vegetation and currently forested areas of the study area.....	15
Fig. 8: Cross-section along the Widawa River in the study area.	16
Fig. 9: Averaged swath profiles orthogonal to the Widawa River in the study area.....	16
Fig. 10: Modern changes of water courses.....	17
Fig. 11: Workflow diagram of the doctoral thesis.	19
Fig. 12: A: Water sampling sites; B: Bog iron ore study sites; C: Prehistoric sites and D: Landscape study sites.	20
Fig. 13: Radiocarbon dates including chronological interpretation.	28

III. List of tables Appendix A

Appendix A, Table A.1: Sampling sites of sedimentological samples.	149
Appendix A, Table A.2: Bulk sediment chemistry of the profiles RYCHNOW12, NAMY02, NAMY03 and NAMY07 comprising MS-, TOC-, TIC-, pH- and EC-values.....	150
Appendix A, Table A.3: Complete record of radiocarbon dates.....	153

IV. List of units

A	ampere	kV	kilovolt	%	percent
a	year	l	liter	s	second
Å	Ångström	mass%	mass percent	σ	sigma
°	degree	m	meter	SI	International system of units
°C	degree Celsius	M	mol	W	watt
g	gram	μS	microSiemens		
K	kelvin	mya	million year		

1. Introduction

The technology of iron smelting originates from the advanced civilization of the Hittite and spread to the northern Central European lowlands at least in the 5th century BCE (Pleiner, 2000; Yalçın, 2000). Until the late Roman period between the 3rd and 4th century CE Silesia became an important center for iron works (Godłowski, 1965), leaving the question when and how iron smelting was introduced to Silesia and whether this region might represent a missing link between the Latène culture and Iron Age cultures of northeastern Europe. Apart from socio-economic, technological and cultural aspects, the introduction of this technology overall required a certain natural setting, such as the availability of the required resources, such as iron ore, wood, clay, water, wheat chaff and possible fluxing agents (Koschke, 2002; Pleiner, 2000). Vice versa this technology also affected the natural environment, in terms of human-induced vegetation and landscape changes as well as pollution (Mighall et al., 2006; Killick and Fenn, 2012). This doctoral thesis aims to contribute to a better understanding of the human-environment interactions initiated through the introduction of early iron smelting to Central Europe. Based on four case studies (sections 5.1, 5.2, 5.3 and 5.4), which follow a *resource approach [A]*, a *landscape approach [B]* and an *environmental approach [C]* (section 4.1), this thesis investigates the main research questions: (i) Did the landscape and the environment of the study area affect the iron smelting abilities of early iron smelters and influence the introduction of this technology and (ii) did the early smelting activities influence the landscape and the environment in the vicinity of the smelting sites?

This doctoral thesis is a cumulative dissertation subdivided into six sections. The introduction (section 1) briefly explains the project setting and background as well as the aims and strategy of this thesis. The state of the art section (section 2) summarizes the general theoretical project integration and gives a broad scientific overview on the main approaches followed in the presented case studies and the research background. The study area section (section 3) gives an overview on the study region and area with further information on its location, topography, geotectonic, climate, soils, vegetation and hydrology. The material and methods section (section 4) structures the general methodical approach and comprehensively presents the conducted field campaigns in 2013 and 2014 as well as the applied laboratory methods in further detail compared to the method sections in the respective case studies. In section 5 four case studies, which represent the basis of this thesis, are presented. While case studies I and II (sections 5.1 and 5.2) investigate the natural environmental potential and the resource

situation towards iron smelting, case studies III and IV (sections 5.3 and 5.4) deal with the induced landscape changes and the immediate environmental and geochemical impacts:

- Case study I (section 5.1) *“Iron, Humans and Landscape – Insights from a Micro-Region in the Widawa Catchment Area, Silesia”*, written with Enrico Lehnhardt, Wiebke Bebermeier and Michael Meyer, is published in the Special Volume 4 (2015) of ‘eTopoi. Journal for Ancient Studies’: Bebermeier, W., Knitter, D., Nakoinz, O. (Eds.). *“Bridging the Gap – Integrated Approaches in Landscape Archaeology”*, Exzellenzcluster 264 Topoi (2016).
- Case study II (section 5.2) *“Bog Iron Ore as a Resource for Prehistoric Iron Production in Central Europe – A Case Study of the Widawa Catchment Area in Eastern Silesia, Poland”*, written with Wiebke Bebermeier, Philipp Hoelzmann and Enrico Lehnhardt, is in press in the Special Issue of Catena: Kluiving, S., Heyvaert, V., Howard, A., Bebermeier, W. (Eds.). *“Geoarchaeology: Human-environment interactions in the Pleistocene and Holocene”*, Elsevier B.V., with a planned publication in 2016.
- Case study III (section 5.3) *“Landscape history since the Saalian Drenthe stadial in the Widawa Catchment Area in Silesia, Poland: A case study on long-term landscape changes”*, written with Wiebke Bebermeier, Philipp Hoelzmann and Brigitta Schütt, is in review for the Thematic Volume of Quaternary International: Mandel, R., Nicoll, K. (Eds.) *“Topics in Geoarchaeology: Reconstructions of Ancient Landscapes and Paleoenvironments”*, Elsevier B.V., with a planned publication in 2016.
- Case study IV *“Geochemical analyses of charcoal piles and rectangular stoves at the Prehistoric Przeworsk iron smelting site Pielgrzymowice in Silesia, Poland”* (section 5.4), written as a work report, is currently not intended for publication.

The final section 6 resumes the results from the case studies and integrates them into the landscape archaeological framework of the research project. At that, this section deals with one of the main research questions of the research project, (i) when iron smelting has been introduced to this region and (ii) what role the resource inventory played in this context.

“Geography is history in space, likewise history is geography in time” (Kosmala, 2013: 19). This statement is written in a contribution on the geographical characteristics of Silesia by Gerard Kosmala (Kosmala, 2013). Whether or not to agree with this statement, it illustrates the close relationship between sciences and humanities in terms of geography and archaeology in landscape archaeological research. Based on this close relationship and the

benefits from a mutual exchange the interdisciplinary landscape archaeological research project (A-5-2) “Iron mining in the Przeworsk Culture” between the Institute of Geographical Sciences and the Institute of Prehistoric Archaeology at the Freie Universität Berlin began its work in 2012. The project was conducted in close cooperation with the Archaeological Institute of the University of Wrocław, Prof. Dr. Artur Błażejowski, and the Museum of Archaeology Wrocław, Dr. Paweł Madera, in Poland. It is a follow-up project of investigations of Przeworsk settlement sites in the southern forelands of the Harz Mountains in Germany (Hoelzmann et al., 2012; Ullrich et al., 2011; Bebermeier et al., 2009) in their area of origin in Poland. The investigated area of this project is situated in Silesia and represents a regional cluster of prehistoric slag sites recorded by the nationwide Archaeological Record Poland (section 3.1; AZP, since 1978). The project is incorporated in the research group (A-5) “Iron as a raw material” in research area A of the Cluster of Excellence Topoi. This research group deals with the introduction and dissemination of early iron smelting technologies in Central and southern Europe.

2. State of the art

2.1 Theoretical integration

This dissertation is integrated into an interdisciplinary project depending on the close collaboration between the scientific disciplines of physical geography and prehistoric archaeology. Therefore, as a theoretical concept, this thesis is also represented by the overlapping fields of landscape archaeological and geoarchaeological research (Brown, 2001).

The term of landscape archaeology, as a beginning of this discipline, came first into use in 1970 (Fleming, 2006). In this discipline humans are put into a broad context of a continuous interaction with the environment (Greene, 1995). In contrast to the field of settlement archaeology, landscape archaeology extends the focus from single settlements to the landscape and spatial contexts in archaeological research (Evans, 2003). In this sense landscape archaeology overall represents a matter of scale, rather than certain applied techniques (Evans, 2003; Kluiving and Guttmann-Bond, 2012). As a discipline it is confronted with a dichotomy between different theoretical concepts of landscape theory and different practical approaches for over two decades (Lock and Harris, 2006). An important aspect for landscape archaeological research is the reconstruction of paleo-environmental and human-environment interactions (Mather and Koch, 2011), applying methods from other fields, such as geophysics and geoinformatics (Greene, 1995; Mather and Koch, 2011; Ullrich et al., 2011). Furthermore, landscape archaeology is also closely connected with the field of environmental archaeology (Kluiving et al., 2012), as it also deals with soil archives, agricultural impacts and resource situations (Greene, 1995).

In contrast, the scientific field of geoarchaeology is broadly characterized by the investigation of archaeological questions and problems applying geoscientific concepts, methods and knowledge (Mandel, 2000; Bebermeier and Schütt, 2011; Canti and Huisman, 2015). In comparison to geoarchaeology the related field of archaeometry focuses on physical and chemical prospections of the material origin (Fuchs and Zöller, 2006). Geoarchaeology, arisen as a collaborative discipline between geology (respectively geomorphology) and archaeology, has a long history dating back to the early 19th century (Rapp and Hill, 2006; Pollard, 1999). As a term it has been increasingly used since the 1970s (Rapp and Hill, 2006), when the magnitude of anthropogenic alterations of the Earth System became more evident (Brown, 2008). It is now also widely perceived as a sub-discipline of archaeological research (Pollard, 1999). As terrestrial and remote geoscientific techniques are extensively used in the field of

geoarchaeology (Rapp and Hill, 2006; Pollard, 1999), it represents a natural-scientific method-based discipline (Joyner, 2005), focusing on stratigraphy, site formation processes and landscape reconstruction (French, 2003; Goldberg and Macphail, 2006). Furthermore, the integrated geochemical approaches of geoarchaeology are commonly used to investigate exploitation and processing techniques of mineral resources, examining “the dynamic relationship between human society and the environment” (Pollard, 1999: 181).

In its theoretical approach this doctoral thesis mainly follows the ideas of Barker and Bintliff (1999), who define geoarchaeology as a natural science that represents an essential element in interdisciplinary landscape archaeological research. Furthermore, it is stated that the greatest challenge in interdisciplinary landscape archaeological research is bridging “the divide between the ecological approaches of the natural sciences to past landscapes, on the one hand, and the concerns of social archaeologists on the other with the interface between human actions and landscape” (Barker and Bintliff, 1999: 209). Following this theoretical perspective, the interdisciplinary introductory case study I (section 5.1) of this doctoral thesis is integrated into the field of landscape archaeology, while the natural scientific case studies II, III and IV (sections 5.2, 5.3 and 5.4) are rather to be dedicated to the field of geoarchaeology, integrated in a landscape archaeological project.

2.2 Geoarchaeological and archaeometallurgical research on bog iron ores and slags in Central Europe

Geoarchaeological and archaeometallurgical research on the history and origin of early iron smelting, which represents the key issue in case study II (section 5.2), began more than a century ago (Pleiner, 2000). Important recent volumes, which summarize the history of early iron smelting in Central Europe, were published in Pleiner (2000), Pleiner (2006) and Hošek et al. (2011), among others. In Central and northern Europe, the beginning of iron smelting was closely connected to the utilization of bog iron ores as a raw material for the early iron production (Evenstad, 1801; Graupner, 1982; Leb, 1983; Brumlich et al., 2012).

As stated in further detail in case study II (section 5.2), bog iron ores are iron-rich consolidated terrestrial accumulations (Graupner, 1982; Sperling, 2003), which gradually form under hydromorphic conditions in clastic sediments with a constant iron-containing groundwater influx (Puttkammer, 2012; Banning, 2008; Landuydt, 1990). Although some aspects of bog iron ores, such as the meaning of its manganese and phosphorus contents on early iron smelting attempts, are part of an ongoing scientific debate (Iles, 2014; Crew, 2011,

Buchwald, 2005), it is common sense that bog iron ores were preferably used for early iron smelting attempts in northern Central Europe (Schwab, 2004; Küster, 1999; Leb, 1983).

For different regions in eastern Central Europe numerous archaeometallurgical studies on various prehistoric smelting sites were conducted (e.g. Pleiner, 1958; Bielenin, 1974; Domanski, 1972; Piaskowski, 1976; Hensel, 1986), also involving many smelting experiments from the 1950s until today (e.g. Bielenin and Suliga, 2008; Thiele, 2010; Puttkammer, 2012; Orzechowski and Przychodni, 2014) in which the origin, distribution and chemical composition of bog iron ores and iron slags in connection to early iron smelting attempts were investigated. Important recent contributions to the formation, distribution and characterization of bog iron ores in Central Europe were published in Landuydt (1990), Kaczorek and Sommer (2003), Kaczorek et al., (2004), Kaczorek et al. (2005), Banning (2008) and Ratajczak and Rzepa (2011).

Important contributions to the field of geochemical investigations of bog iron ores and slags from Central Europe were published in Joosten et al. (1998), Puttkammer (2012) and Brumlich et al. (2012), among others. A relatively young approach in archaeometallurgical research in Europe is the geochemical provenance research of prehistoric iron objects and slag fragments. Applied approaches in this field are (i) correlation of different element concentrations and ratios in iron slags (Buchwald and Wivel, 1998; Heimann et al., 2001; Schwab et al., 2006; Paynter, 2006; Blakelock et al., 2009; Jouttijärvi, 2013; section 5.2), (ii) application of the principal component analysis on the element composition (Charlton et al., 2010; Charlton et al., 2012; section 5.2) and (iii) analysis of Pb, Sr and Os isotope concentrations in iron slags (Degryse et al., 2009; Brauns et al., 2013; among others).

2.3 Research on landscape reconstruction

The scientific field of landscape reconstruction, which is the main topic in the landscape case study III (section 5.3), is one of the most important objectives in geoarchaeological research (French, 2003) and a means to predict site location, age and preservation in a [reconstructed] landscape (Holliday, 2004) in order “to explain changes that occurred to human cultures over time” (Waters, 2000: 537). One of the main problems in landscape reconstruction is that many geomorphic systems have a non-linear nature that impedes the reconstruction of initial conditions from the end products (Bell and Walker, 2005). This is also true when linking the reconstruction of human landscape impacts to the context of early iron production in terms of mining activities (Pollard, 1999; Garner, 2011) and deforestation induced erosion events (Joosten et al., 1998; Fairbridge, 2009; James et al., 2013). It is widely accepted that the

introduction of iron smelting most notably affected the natural environment of European landscapes (Pollard, 1999; Garner, 2011; Joosten et al., 1998). Above all, the exploitation of natural resources in terms of mining and deforestation, particularly iron ores and wood for charcoal production, triggered changes in the natural system (Mighall et al., 2006). Furthermore, new tools allowed new land-use practices and strategies, which also affected the landscape budget (Kalis et al., 2003). Nevertheless, depending on the scale of early mining and smelting activities landscape changes are typically rather set in the context of agriculture (Sommer, 2006; Mighall et al., 2009) than iron production (Garner, 2011; Harrison et al., 2010).

In previous research various methods reconstructing landscapes on different scales exists with a particular focus on topography, hydrology, palynology, geophysics, sedimentology and pedology, often combining archaeological and geomorphological approaches (French, 2003; Driese, 2009; Berking et al., 2011; Blättermann et al., 2012; Hirsch et al., 2015; Draganits et al., 2015). In younger approaches these different data sets are combined with each other in geoinformation systems (French, 2003), involving different landscape reconstruction algorithms, such as virtual (3D) reconstructions, based on historical, geological and LiDAR data (Werbruggen et al., 2011; Pacina et al., 2015; Ivanišević and Bugarski, 2015; Draganits et al., 2015; Brown, 2008; Schneider et al., 2015; section 5.3).

2.4 Early human-environment interactions in Silesia

Early interactions of humans and their environment, as these are the key topic in all presented case studies (sections 5.1, 5.2, 5.3 and 5.4), are the subject of many investigations in the scientific fields of geoarchaeology, geology, palynology and soil science, among others on the broad scale of Central Europe (Dotterweich, 2013; Verstraeten, 2014). Methodically often very different approaches are followed in order to quantify, model and present early human impacts on the landscape and the environment (Verstraeten, 2014). On the European scale the beginnings and the intensities of human-induced landscape changes are often very variable, depending on the climate, the technological development and the population pressure (Dotterweich, 2013).

In Silesia earliest evidence of human settlements is dedicated to the Middle Paleolithic (Burdukiewicz, 2003). According to the AZP (since 1978) archaeological finds can be dedicated to all cultural periods from the Paleolithic Period to the Bronze and Iron Age (section 5.3; Bykowski, 1997). In contrast, research on early human-environment interaction lacks on the local scale but is available in terms of sedimentological and palynological studies

for the wider region of Silesia. Investigations of sediment archives in Lower Silesia showed a first human impact during the warmer period of the Mesolithic (Wiśniewski et al., 2013). A study of alluvial fan deposits at the Glubczyce Plateau in southeastern Silesia assigned the beginning human impacts to the Neolithic – when agriculture with regionally very different intensities expanded – and to the Bronze Age – when it further intensified (Zygmunt, 2009). Also paleo-ecological studies, involving pollen data in southeastern Central Poland, assigned the beginning of early human impacts to the Middle Neolithic and showed an intensification during the Bronze Age (Pawłowski et al., 2014). Furthermore, investigations by Klimek (2010) of the foresudetic loess plateau in southern Silesia dedicate early human-induced erosion events to Neolithic settlement activities. Accordingly, Wójcicki and Marynowski (2012) describe an initiated pressure on natural forest vegetation in southeastern Silesia during this period, which distinctly intensified during the Bronze Age and Iron Age. Such intensifications of early human impacts with the beginning of the Iron Age and the Roman period are also stated by Pawłowski et al. (2014) and Zygmunt (2009).

2.5 Beginnings of iron smelting in the Przeworsk culture

The Przeworsk culture, which represents the cultural setting of all presented case studies (sections 5.1, 5.2, 5.3 and 5.4), was a Central European cremation burial culture during the Iron Age and the Roman period from the late 3rd century BCE and the 5th century CE (Dąbrowska, 2003; Godłowski, 1965), which had their primary distribution area in the broad region from the middle Danube, to the upper Oder and Vistula region of eastern Central Europe (Todd, 2004; Meyer, 2008). Early iron smelting attempts of this culture in Eastern Silesia were “almost solely” (Orzechowski, 2011: 41) based on the technology of bloomery shaft furnaces with a slag pit (Orzechowski, 2007; Woźniak, 1978). While numerous publications have dealt with iron smelting in the Przeworsk culture during the pre-Roman Iron Age and Roman period with thousands of bloomery furnaces and huge production centers (Godłowski, 1985; Pleiner, 2000; Dąbrowska, 2003; Orzechowski, 2007; Orzechowski, 2011; among others) – giving the Przeworsk culture the name “culture of iron” (Orzechowski, 2007: 27) – little is known on the introduction of this technology to the Przeworsk culture.

The iron smelting technology developed during the 2nd millennium BCE in the territory of the Hittite culture and was then gradually spread all over Europe (Pleiner, 2000; Yalçın, 2000). During the 5th century BCE this technology reached the Black Forest (Gassmann, 2005; Gassmann et al., 2012) and southern Brandenburg, Germany (Brumlich et al., 2012), as well as Central Jutland, Denmark (Matthissen, 2011; Olesen, 2010), before it arrived in Silesia,

Poland, in approximately the 2nd century BCE (Madera, 2002). In the distribution area of the Przeworsk culture in Greater Poland (Siciński, 1996; Woźniak, 1978) and Mazovia (Woyda, 1977; Woyda, 2002) iron smelting was conducted at least since the turn of the eras, followed by larger scaled production centers in the Holy Cross Mountains (Pleiner, 2000; Orzechowski and Suliga, 2007; Orzechowski, 2013). For Silesia Woźniak (1978) states small-scale smelting activities during the early Roman period and Godłowski (1965) describes that this region represented an important center for iron works during the 3rd and 4th century CE (late Roman period), leaving a temporal and spatial gap between the introduction of iron smelting to Central Europe and the development of larger production centers of the Przeworsk culture.

3. Regional setting and study area

The regional focus is set on the Widawa catchment area, which is situated in the region of Silesia, located in southwestern Poland, Central Europe (Fig. 1A). This region is represented by various spatial extents, depending on the perspective, which can be historical, cultural, geographical, political or administrative (Kosmala, 2013). Silesia can be divided into the western Lower Silesia and the eastern Upper Silesia. For this study the term Silesia is referred to as the current extents of the Polish voivodeships Opole and Lower Silesia (Fig. 1B), equivalent to the area of Silesia presented in the Atlas Śląska (Pawlak, 1997).

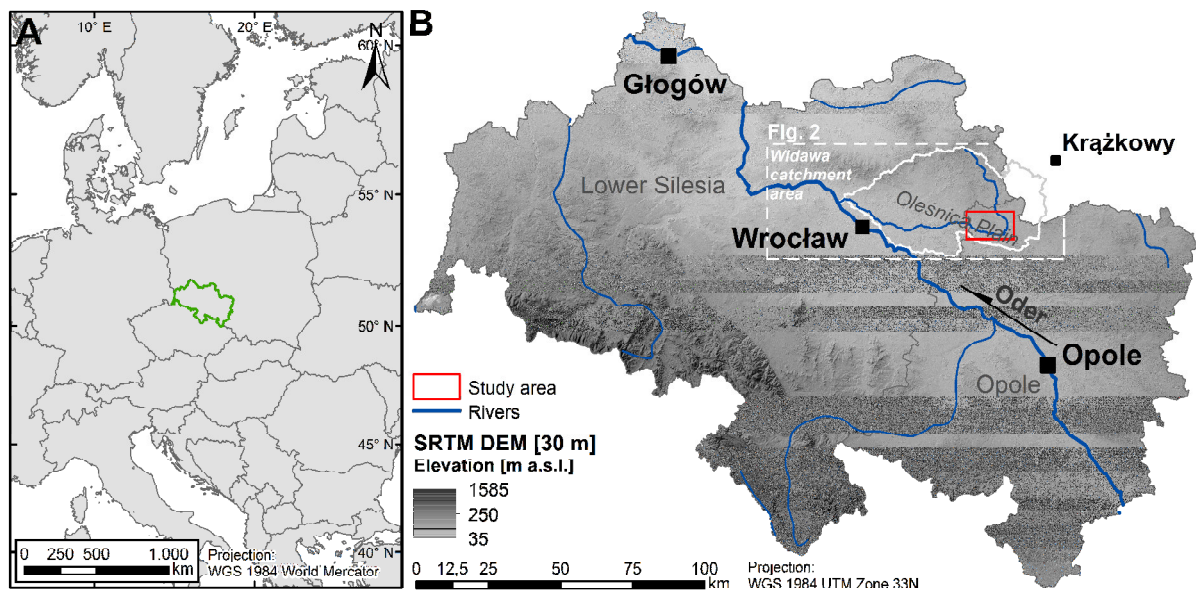


Fig. 1: A: Location of Silesia, Poland; B: Location of the Widawa catchment area and the study area in the region of Silesia.

Data: Fig. 1A: Country borders from Natural Earth Data (2013), extension of the region of Silesia from Global Administrative Areas (2013); Fig. 1B: Digital elevation model with a horizontal resolution of 30 m (1-arc second) from USGS (2000) SRTM data; rivers from Natural Earth Data (2013) and KZGW (2015) and Widawa catchment area from KZGW (2015).

The region of Silesia is delimited by the regions of Lusatia (Germany) to the west, Greater Poland to the north, Lesser Poland to the east and Bohemia and Moravia (Czech Republic) to the south (Kosmala, 2013). The main drainage of Silesia is the Oder River, flowing from southeast to northwest (Fig. 1B). The northwestern part of Silesia is characterized by flat lowlands of the Oder River basin, the Silesian lowland, which represents in its central part the Wrocław-Magdeburg glacial valley (Liedtke, 1981). To the south the region is delimited by the Sudetes, fault-block mountains, formed in the Cenozoic era with Paleozoic features (Kosmala, 2013), which represent the border between Poland and the Czech Republic (Fig. 1).

In the northeast of Silesia – at the border between the Voivodeships Opole and Lower Silesia – the catchment area of the Widawa River is situated (Fig. 1B). This catchment area is to the south delimited by the Oder glacial valley of the Warthe stadial of the Saalian glaciation (Liedtke, 1981) and to the north by the Trzebnica Ridge (Wał Trzebnicki; Kuszell et al., 2007), a terminal moraine of the Warthe stadial (Liedtke, 1981). The Widawa River first flows southwards from the Trzebnica Ridge and then from Namysłów on westwards following the Oleśnica Plain and entering the Oder River in the northwest of Wrocław (Fig. 2).

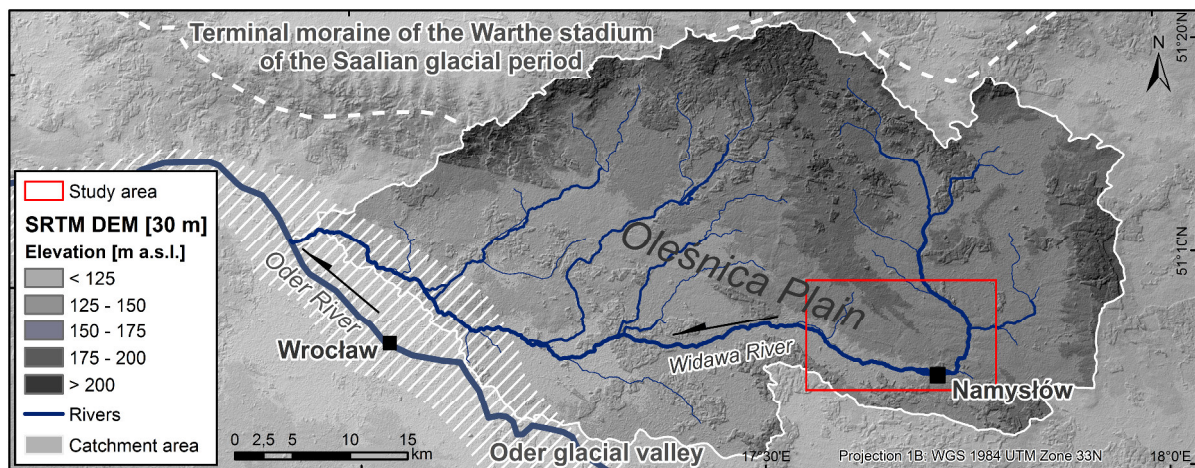


Fig. 2: Widawa catchment area.

Data: Digital elevation model with a horizontal resolution of 30 m (1-arc second) from USGS (2000) SRTM data; Widawa catchment area from KZGW (2015); rivers from Natural Earth Data (2013) and KZGW (2015) and Oder glacial valley and terminal moraine from Liedtke (1981).

3.1 Study area

The study area is situated in the southeast of the Widawa catchment area in the eastern part of the Oleśnica Plain (Fig. 2; Kuszell et al., 2007). The area contains a cluster of prehistoric slag sites recorded by the AZP (since 1978). Being situated along the Widawa floodplain, this cluster is concentrated to the area of the Michalice Reservoir (Fig. 3), which was dammed in 2001 (Wiatkowski et al., 2010). The relatively flat landscape of the study area with heights between 137 and 187 m above sea level (a.s.l.) is characterized by flat landforms with hillslopes mostly below 1° and extremely rarely exceeding 5° . Steeper natural slopes only occur at former undercut banks at the margins of the Widawa floodplain and never exceed 20° . Most slopes of the study area are exposed towards south and north rather than west- and eastwards (Fig. 3; CODGiK, 2013).

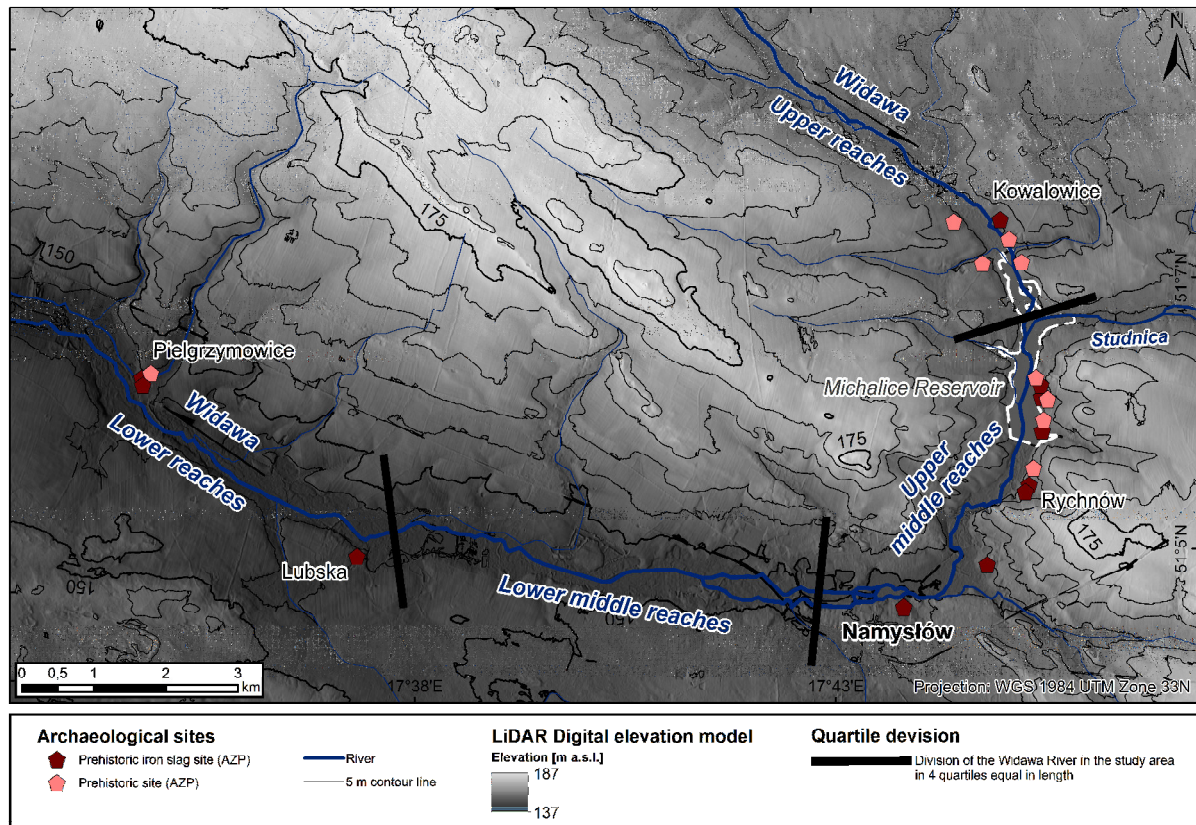


Fig. 3: Topography of the study area.

Data: Digital elevation model derived from GODGiK (2013) LiDAR DEM with 1 m horizontal resolution; archaeological sites from AZP (since 1978) and rivers from KZGW (2015).

3.2 Geotectonic and geological setting

Geotectonically, the study area is situated in the northeast of the fore-Sudetic monocline, a foredeep of the southwestern Sudetic mountain range (Pelzer, 1991). The tectonic disturbances framing the Sudetic Basin – situated in Central Silesia – show mostly a Hercynian orientation from west-northwest to east-southeast. In contrast, the tectonic disturbances of the study area in the northeast of the Sudetic Basin are striking Variscan, from northeast to southwest (Fig. 4; Ziegler, 1990). The geological subsurface without Cenozoic deposits mostly consists of 200 to 235 mya old Keuper deposits, but also older Buntsandstein and Muschelkalk deposits in the southwest and younger Lias deposits in the northeast of the catchment area (Fig. 4; Dadlez et al., 2000), showing successively older deposits in southwestern direction. In the study area, on top of these deposits up to 35 m thick Upper Miocene formations of the Cenozoic were deposited, before up to 60 m thick Quaternary deposits accumulated (Bartczak, 1997). The Quaternary landscape history is described in further detail in case study III (section 5.3).

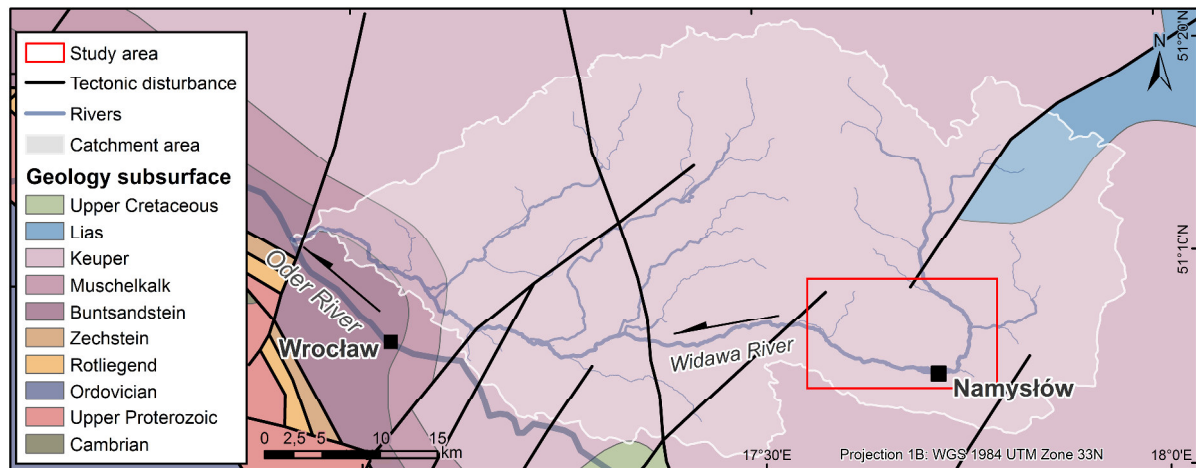


Fig. 4: Tectonic faults in Paleozoic and Mesozoic deposits in the catchment area of the Widawa.

Data: Tectonic faults and geological deposits including color scheme without Cenozoic from Dadlez et al. (2000); Widawa catchment area from KZGW (2015) and rivers from Natural Earth Data (2013) and KZGW (2015).

3.3 Climate

The climate of the study area is characterized by a cold temperate, all-year humid continental Dfb climate (Köppen, 1931 cited after Kuttler, 2009; Climate-data.org Namysłów, 1982-2012). Regionally, between Wrocław, Opole and Krązkowy (Fig. 1B), the temperatures average between -2.6 °C and 18.0 °C with maximal temperatures at Krązkowy (Climate-data.org Krązkowy, 1982-2012). The regional annual precipitation totals between 551 mm at Wrocław and 611 mm at Opole, pointing to an increasing precipitation in eastern direction and a slightly increasing annual temperature variance in northeastern direction (Climate-data.org Wrocław/Opole/Krązkowy, 1982-2012). Further information on the climate is stated in case study I (section 5.1).

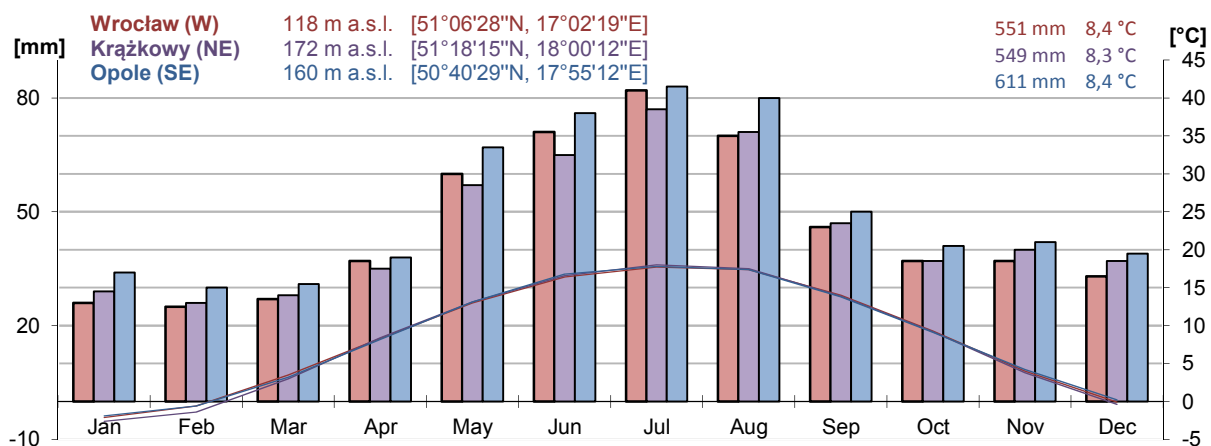


Fig. 5: Regional climate variance in the region of the study area.

Data: Climate data of Wrocław, Krązkowy and Opole from Climate-data.org (1982-2012).

3.4 Soils

According to the Atlas Śląska the soils of the study area are mainly comprised of albeluvisols, but also dystric cambisols, chernozems and ferric podzols (Pawlak, 1997). Along the upper Widawa floodplain there are fluvisols and along the lower floodplain there are arenic fluvisols. Further marginal soil types are stagnosols in the north of the Michalice Reservoir and cambisols in the south of the built-up areas of Namysłów (Fig. 6; Pawlak, 1997, map sheet 28). Especially the chernozems, albeluvisols and cambisols represent regionally particularly fertile soils, suitable for wheat cultivation (Pawlak, 1997, map sheet 34).

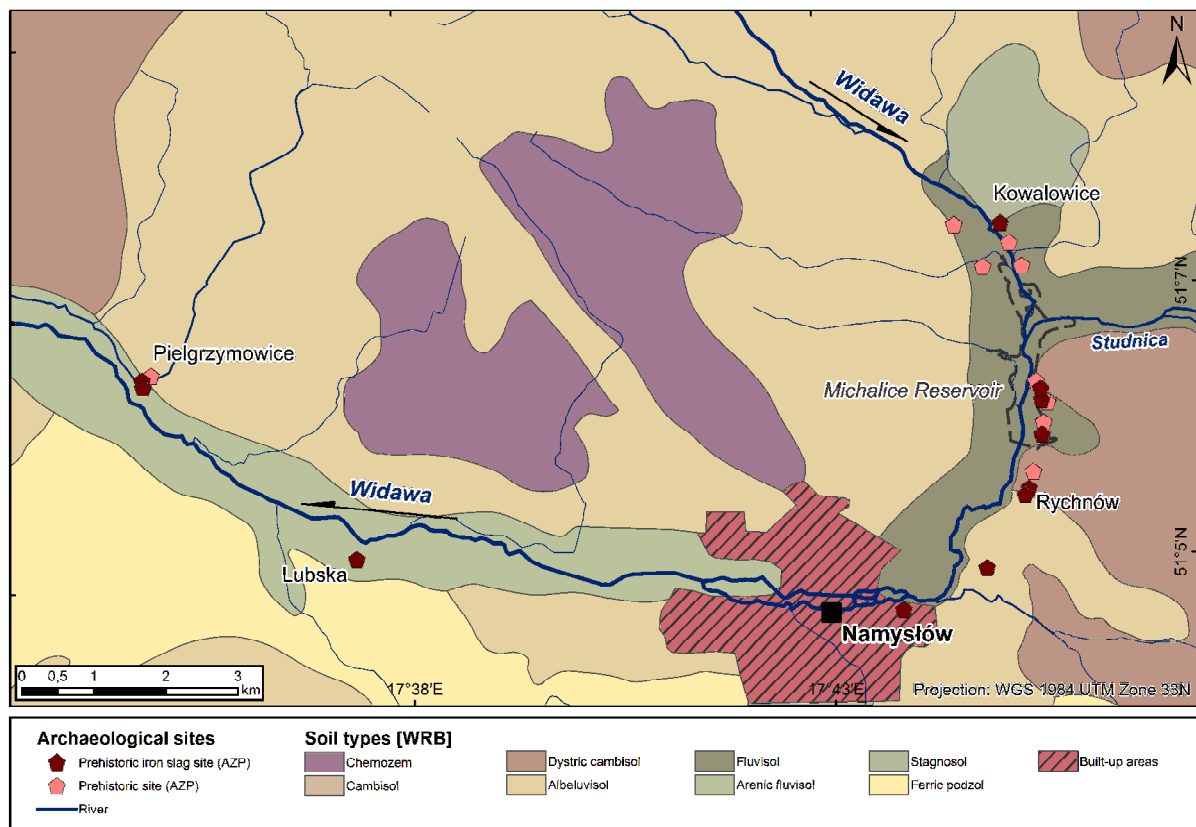


Fig. 6: Soil types of the study area.

Data: Soil types from Pawlak (1997), map sheet 28 translated according to WRB (Ad-Hoc-AG Boden, 2005); archaeological sites from AZP (since 1978) and rivers from KZGW (2015).

3.5 Vegetation

At least since 1780 the forests of the study area are almost fully cleared and the area has been intensively agriculturally used (Orczewska, 2009). Today only very small parts of the area – mainly situated in the south of the Widawa catchment area – are covered by forest areas (Fig. 7). Nevertheless, the variety of different environmental conditions in regard to soil types and moisture allowed a reconstruction of the natural potential vegetation of the study area. According to the Atlas Śląska the natural vegetation was mainly dominated by meager mid-

European oak-hornbeam woodlands (Pawlak, 1997). Furthermore, in equal shares the potential vegetation also showed ash-alder and ash alluvial forests along the Widawa floodplain and fertile mid-European oak-hornbeam woodlands. Rather marginally the vegetation potentially consisted of mid-European acidophilic sessile oak woodlands of the lowlands in the south and elm-alluvial forests along the tributary valleys in the northern part of the study area (Fig. 7; Pawlak, 1997, map sheet 52).

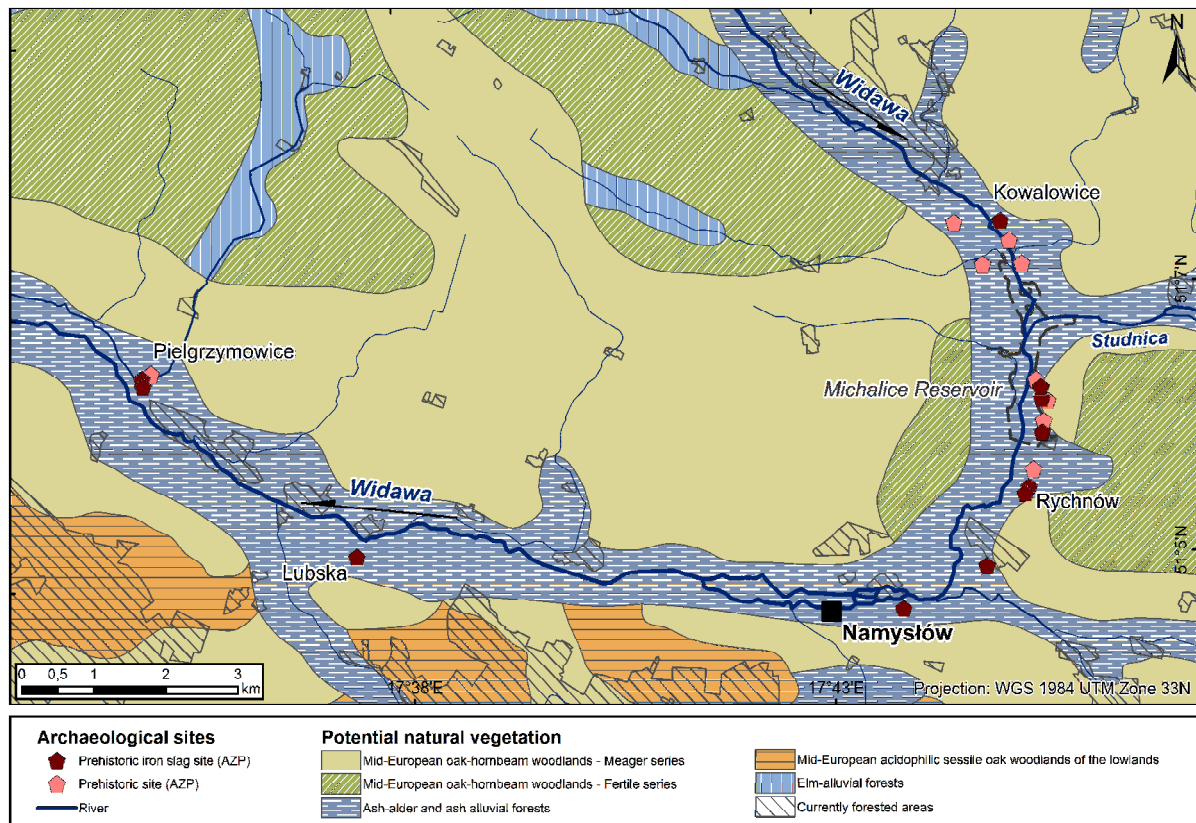


Fig. 7: Potential natural vegetation and currently forested areas of the study area.

Data: Potential natural vegetation from Pawlak (1997), map sheet 52, archaeological sites from AZP (since 1978); rivers from KZGW (2015) and currently forested areas from Geofabrik (2015).

3.6 The Widawa River, its hydrology, morphometry and younger history

The name Widawa of the main drainage of the study area comes from the proto-slavish word “vid”, to spin, and refers to the meanders, which particularly characterize the lower reaches of the Widawa (Kempa and Hełdak, 2011). The Widawa and the Studnica River (Fig. 3), as the two major rivers of the catchment area, are perennial drainage regimes (Wdowikowski, 2014). The Widawa river system can be described as highly regulated, particularly in its middle and lower reaches (Kasperek et al., 2013).

In absolute measures, according to data from KZGW (2015) the Widawa has a length of 109.8 km and an average discharge of 6.95 m³/s at Wrocław (Kasperek et al., 2013). With an

elevation between 225 and 110 m a.s.l. from source to mouth (USGS, 2000) it has an average gradient of 105 mm / 100 m (0.105 %). Its catchment represents an area of approximately 1750 000 km² with a river density of 0.61 km/km² calculated with data from KZGW (2015). Within the boundaries of the study area (Fig. 3) the Widawa has an elevation between 139 and 157 m a.s.l. with an average gradient of 68.2 mm / 100 m (0.068 %) on a length of 26.4 km. This gradient is characterized by three main weirs, at Michallice, Namysłów and Dębnik, which impound the Widawa to up to 3 m, and a number of smaller dam structures (Fig. 8).

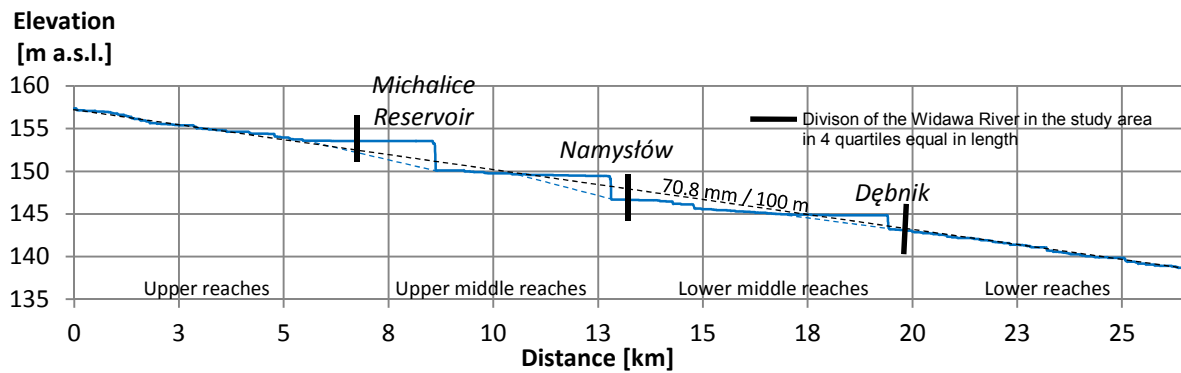


Fig. 8: Cross-section along the Widawa River in the study area.

Data: Relief of the cross-section derived from GODGiK (2013) LiDAR DEM with 1 m horizontal resolution; location of the Widawa River from KZGW (2015).

Divided into four sections from the upper to the lower reaches of the study area (Fig. 3 and 8) the average valley forms of the Widawa show varying characteristics. In the upper two sections the Widawa valley is comparatively narrow. In the third section the valley opens up distinctly and is mostly characterized by a saucer-shaped valley form. In the fourth section the Widawa valley is further incised, mostly showing a slightly deepened saucer-shaped valley (Fig. 9).

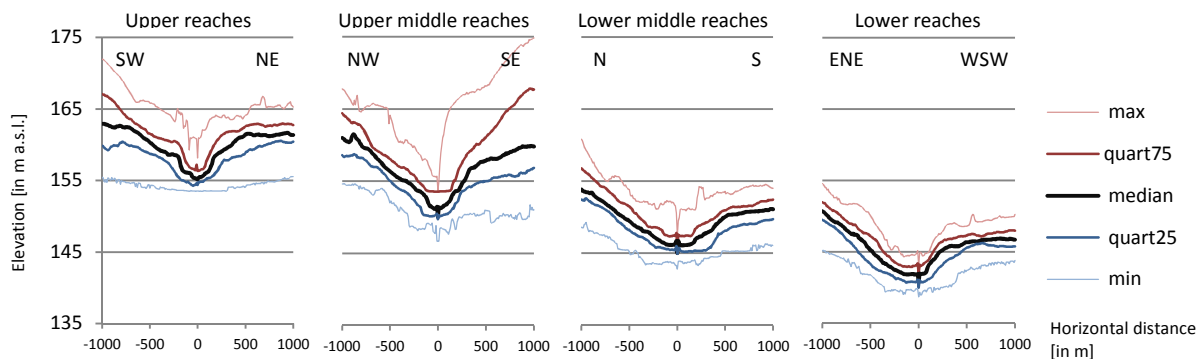


Fig. 9: Averaged swath profiles orthogonal to the Widawa River in the study area.

Data: Location of the Widawa and averaged orthogonal cross-sections derived from GODGiK (2013) LiDAR DEM with 1 m horizontal resolution and the location of the Widawa River from KZGW (2015), according to Hergarten et al. (2014) applying the QGIS Plugin Swath Profile 0.1.1 of Krumbach (unpublished) with measurements every 5 m, an observation buffer of 1000 m and an orthogonal sample density of 10 m.

Particularly during the last 1.5 centuries, when the Widawa river system began to be recorded in accurate topographic maps, continuous distinct anthropogenic changes of the water surfaces – the Widawa River, its tributaries, channels and reservoirs – were documented in the study area (Fig. 10; TK25, 1886-1938; TK50, 1992; CODGiK, 2013). The conducted hydrologic engineering measures comprise the construction of channels, melioration measures, river regulations, especially along the main Widawa valley, and the construction of reservoirs and ponds. Between the end of the 19th century and the beginning of the 20th century parts of these measures, particularly the construction of small channels along the agriculturally used fields, were already conducted (Fig. 10). Until 1992 this system of channels was complemented and the Widawa River was further straightened. During the last two decades the water surfaces were supplemented by artificial lakes and reservoirs, such as the Michalice Reservoir (Fig. 3; TK25, 1886-1938; TK50, 1992; CODGiK, 2013).

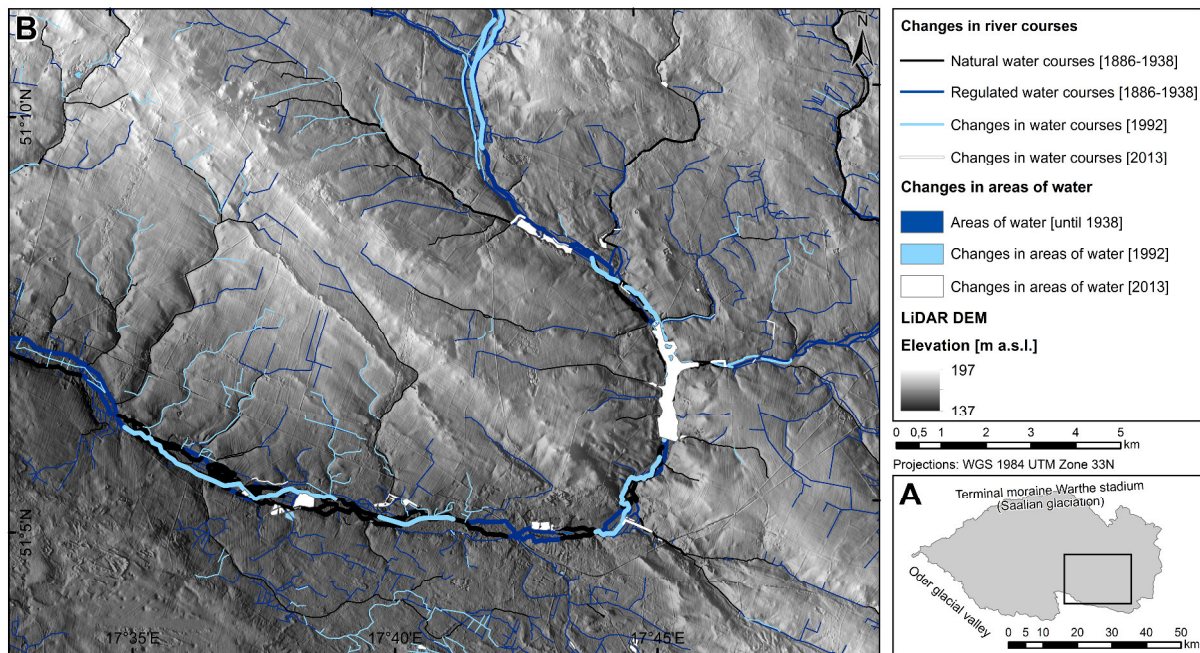


Fig. 10: Modern changes of water courses.

Data: Digital elevation model, Widawa watershed and hillshade (z-factor 3) derived from downscaled LiDAR-data from CODGiK (2013) with a horizontal resolution of 10 m; rivers, lakes and reservoirs 1886-1938 from TK25 (1886-1938), 1 : 25 000; rivers, lakes and reservoirs 1992 from TK50 (1992), 1 : 50 000; rivers, lakes and reservoirs 2013 from CODGiK (2013).

4. Material and methods

Complementary to each method section documented in the respective case studies (sections 5.1, 5.2, 5.3 and 5.4), in this section the general approach is presented in further detail in order to record the complete methodological strategy and procedure of this doctoral thesis.

4.1 General approach

Integrated into the interdisciplinary landscape archaeological Topoi research project A-5-2 the general methodical approach of this dissertation is based on the close collaboration between the Institute of Prehistoric Archaeology and the Institute of Geographical Sciences at the Freie Universität Berlin. This close partnership begins with the mutual selection of the study area, involves the exchange of samples and results and finally enables the possibility of common conclusions (Fig. 11). With the focus on reciprocal human-environment interactions, the methodical strategy of this thesis follows three connected approaches:

(i) In regard to the implications of the natural settings this thesis follows an interdisciplinary landscape archaeological approach (section 5.1) involving a geoarchaeological strategy (section 5.2) with a *focus on the resource situation [A]* (Fig. 11). This approach involves the geochemical and mineralogical analysis of slags and ores, mostly following Joosten et al. (1998) and Kaczorek and Sommer (2003). (ii) Regarding the influence of early iron smelting on the landscape the methodology follows a geoarchaeological approach (section 5.3) dealing with the *reconstruction of the landscape development [B]* (Fig. 11) since the Saalian glacial maximum. This approach is based on Gebhardt et al. (2011) and focuses on the sediment archives, the topography and the geology. (iii) In terms of *environmental impacts [C]* (Fig. 11) of early iron smelting also a geoarchaeological approach (section 5.4) is followed, dealing with the geochemical sediment characteristics in the context of an archaeologically excavated iron smelting site. This approach was mainly based on Hoelzmann et al. (2012).

The fieldwork (section 4.2) and laboratory analyses (section 4.3) of these approaches, distributed over four case studies, each follow an individual strategy. Regarding the general approach, the outcomes of these case studies are connected with each other as well as with the outcomes of the archaeological work to summarized general conclusions on the requirements and impacts of the introduction of early iron smelting in the Widawa valley (Fig. 11).

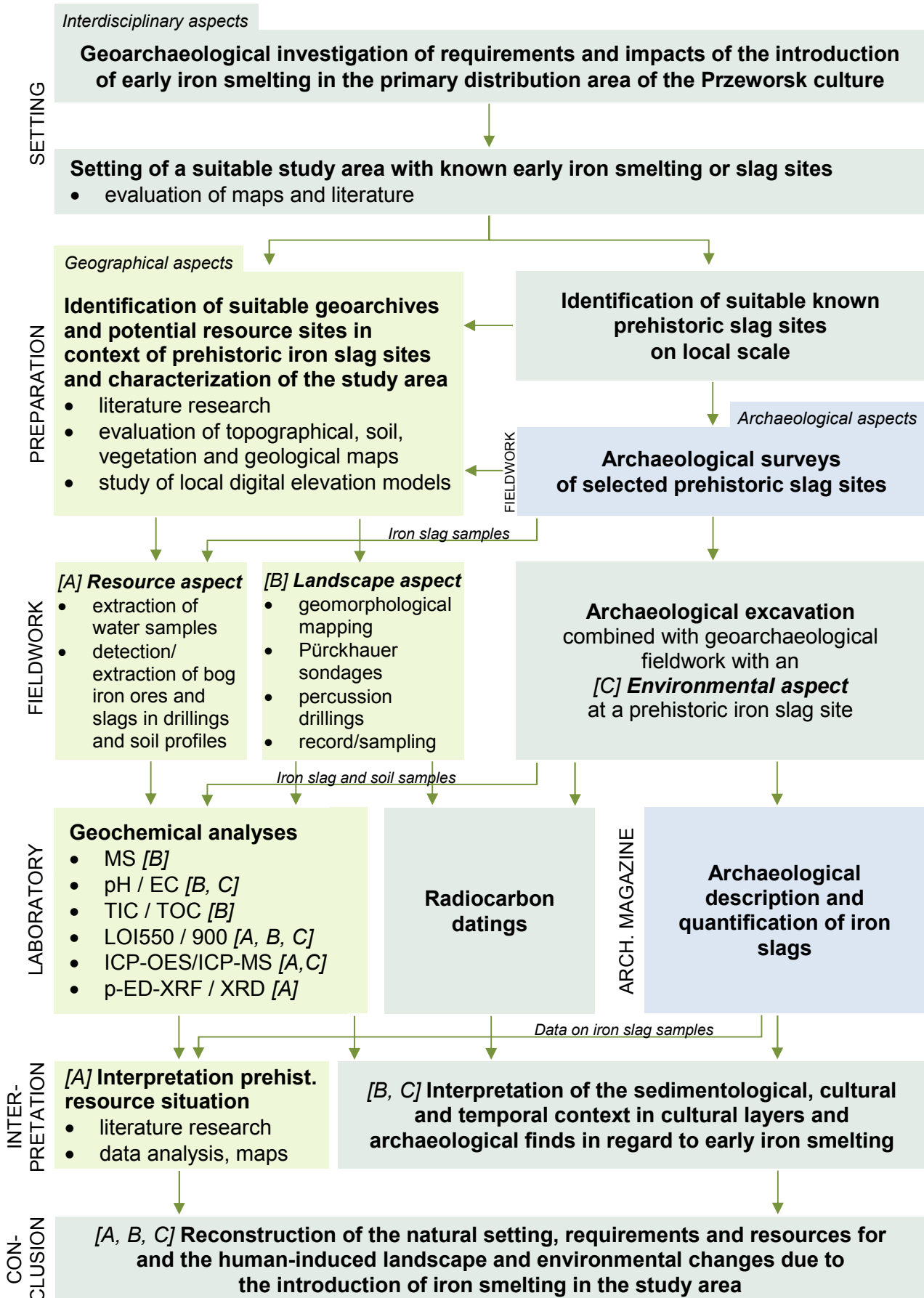


Fig. 11: Workflow diagram of the doctoral thesis.

Data: Modified after Schneider (2014); Gebhardt et al. (2011) and Brückner and Vött (2008).

4.2 Field work

Fieldwork was conducted in two field campaigns in 2013 and 2014. For the *resource approach [A]* (Fig. 11; sections 5.1 and 5.2), in order to investigate the favorability and variability of the ores, water samples were taken from different receiving waters and several sites of the Widawa River (Fig. 12A) and cooled in closed specimen containers to evaluate the iron and manganese contents of different sub-catchment areas (section 5.1). To investigate the present and prehistoric resource inventory (initial) in- and ex-situ bog iron ores were collected from the surface, two Pürckhauer sondages and two percussion drillings at different sites of the study area with and without archaeological find context (Fig. 12B). Moreover, prehistoric iron slags were collected from slag sites of the pre-Roman Iron Age and early Roman period during the archaeological surveys (Fig. 12C; Appendix B, Table A.1).

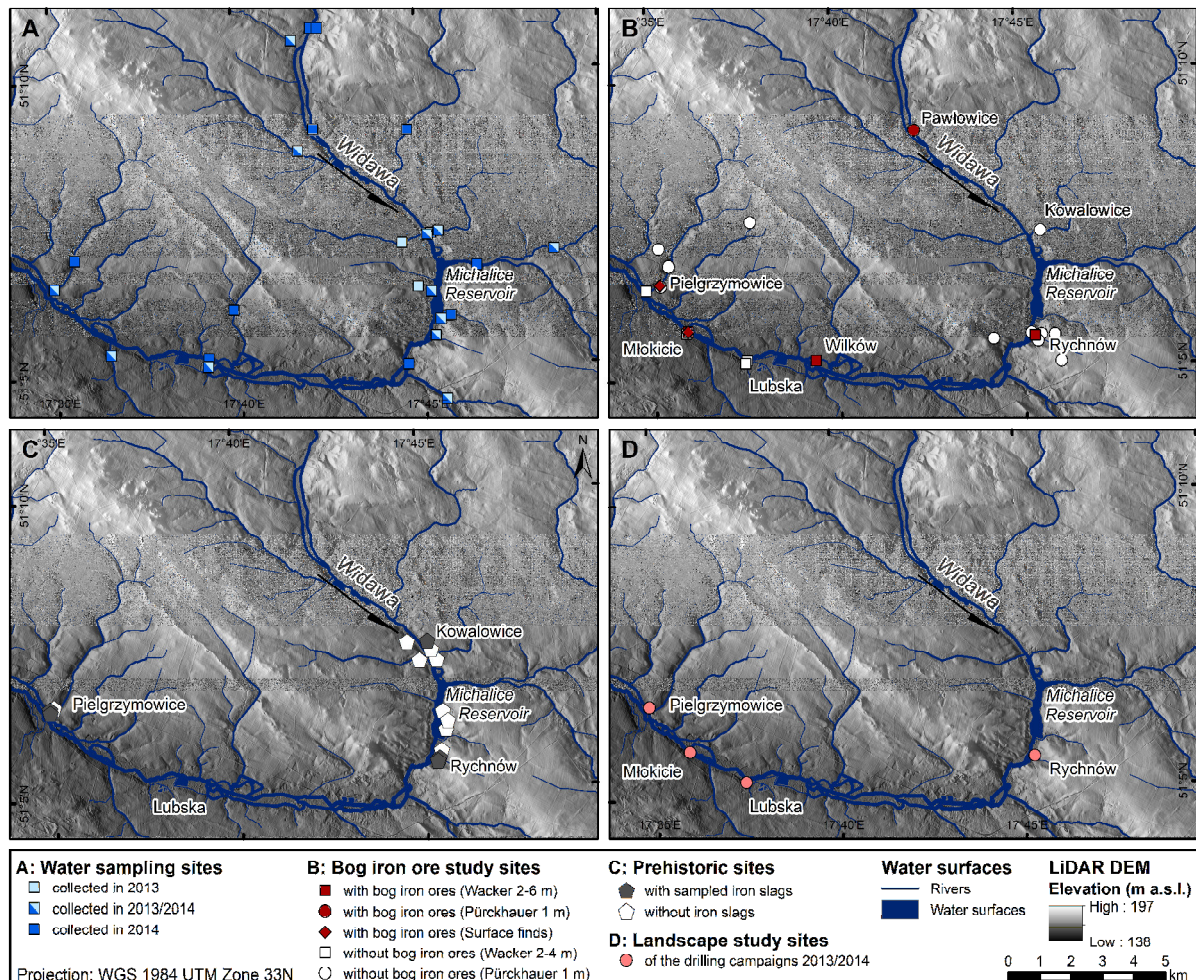


Fig. 12: A: Water sampling sites; B: Bog iron ore study sites; C: Prehistoric sites and D: Landscape study sites.

Data: Digital elevation model derived from GODGiK (2013) LiDAR DEM with 1 m horizontal resolution; prehistoric sites with and without iron slags from AZP (since 1978); rivers from KZGW (2015).

In the framework of the *landscape approach [B]* (Fig. 11; section 5.3) a minimally invasive strategy was applied, which consisted of geomorphological mappings according to Leser and Stäblein (1985) and percussion drillings at the study sites of Rychnów, Lub ska, Młokicie and Pielgrzymowice (Fig. 12D). The drillings consisted of five transects of 16 percussion drillings in depths of 2 to 6 m below surface (b.s.; with 60 drilling m in total), using a Wacker drilling hammer (BHF 30 S) with a 5 cm core diameter in an open or closed driving core system (Appendix A, Table A.1). The investigations were based on sedimentological field records according to the German Pedological Mapping Guide (Ad-Hoc-AG Boden, 2005). Apart from grain size, soil color, taken in accordance to the Munsell Soil Color Chart (Munsell, 2000), calcium carbonate and organic content, moisture, sediment texture, rooting, hydromorphic also special features, such as charcoal, macroplant remains, shell or ceramic fragments, were investigated. Soil samples were extracted every 2 to 19 cm, depending on the stratigraphy.

In the *environmental approach [C]* (Fig. 11; section 5.4), in the context of the archaeological excavation at Pielgrzymowice, the location of five geomagnetic anomalies was investigated by two orthogonal Pürckhauer transects of 6 and 11 Pürckhauer drillings and in two vertical and two horizontal excavation sections in the archaeological trenches. For the Pürckhauer drillings phosphate spot tests (Gundlach, 1961) after Feigl (1960) were conducted in samples from 33, 53, 73 and 93 cm b.s. (section 4.3.7). The investigations included sedimentological field records according to the German Pedological Mapping Guide (Ad-Hoc-AG Boden, 2005) following the *landscape approach [B]* and extraction of soil samples every 5 to 10 cm.

All coordinates were determined by an averaged positioning over 5 minutes using the non-differential, hand-held Garmin GPS-devices GPS 60 and GPSmap 60Cx.

4.3 Laboratory analyses

In the following section, the laboratory strategy of each approach is described, while in sections 4.3.1 to 4.3.10 the accurate laboratory proceeding for each method is presented. Prior to the measurements of each sediment, ore and slag sample the samples were air-dried at 30 °C for 48 consecutive hours, the sediment samples were additionally sieved with a 2 mm sieve and all samples were homogenized to a particle diameter of ~1-10 µm using a vibratory disc mill with an agate grinding set for 3 minutes.

For the general *resource approach [A]* (Fig. 11; section 5.1) the water samples were measured with inductively coupled plasma optical emission spectrometry (ICP-OES; section 4.3.1). For the geochemical analysis of bog iron ores and iron slags (section 5.2)

internal standard calibration material for the portable energy dispersive X-ray fluorescence spectrometry (p-ED-XRF) was measured for eight selected (initial) bog iron ore and eight selected iron slag samples applying inductively coupled plasma mass spectrometry (ICP-MS) at the German Mining Museum Bochum (section 4.3.2). This internal standard material was subsequently used for calibrating the p-ED-XRF in order to measure further ore and slag samples at the laboratory of geographical sciences of the Freie Universität Berlin (section 4.3.3). A mineralogical analysis of the ore and slag samples was conducted by X-ray powder diffraction (XRD; section 4.3.4).

For the *landscape approach [B]* (Fig. 11; section 5.3) sedimentological and geochemical analyses were conducted at transect Rychnów I for the profiles RYCHNOW12, NAMY02, NAMY03 and NAMY07, as this study site represents the key site. These analyses consisted of magnetic susceptibility (MS; section 4.3.5), pH values, electrical conductivity (EC; section 4.3.6), loss on ignition (LOI) at 550 and 900 °C and total inorganic (TIC) and organic carbon (TOC) contents measured for selected samples (section 4.3.8; Appendix A, Table A.2). The samples of profile NAMY01 at transect Rychnów I were not geochemically investigated in the laboratory as this drilling represents a parallel drilling of NAMY02. For a selection of 12 samples from transect Lubska the particle grainsize was measured by laser diffraction (section 4.3.9; Appendix C – Case study III, section A.2). For the dating of depositional ages of sediment layers of the drilling profiles the radiocarbon (^{14}C) dating method was applied (section 4.3.10).

For the *environmental approach [C]* (Fig. 11; section 5.4) the phosphate contents of samples from the Pürckhauer transects and excavation sections (section 4.3.7) and the pH values (section 4.3.6), the LOI at 550 and 900 °C, the total carbon (TC) contents (section 4.3.8) and the element composition of major elements applying ICP-OES (section 4.3.1) were determined for samples from the excavation sections. The TOC contents were estimated from the LOI and derived from the TC, as TIC lacks in the collected samples.

4.3.1 Inductively coupled plasma optical emission spectrometry

The ICP-OES allows the measurement of element concentrations digested in a solution through the respective characteristic optical emission spectrum of each measured element from an inductively coupled plasma (Hou and Jones, 2000). The measurements were conducted at the laboratory of the Department of Earth Sciences at the Freie Universität Berlin using an ICP-OES Spectrometer Optima 2100 DV of Perkin Elmer. Prior to the measurements the water samples were acidulated with 0.1 ml 65 % nitric acid and the EC was

measured using a handheld HANNA instruments HI 98301 DiST® 1 TDS Tester. Subsequently the water and soil samples were digested with aqua regia ($\text{HNO}_3 + 3 \text{HCl}$) in order to destroy the existing binding forms and to dissolve the elements in the solution. For the measurement the sample material was diluted in 100 ml stock solutions with a concentration of 10 mg/l. The argon plasma heated the dissolved samples to 6000 to 8000 K and the element contents of the major elements (calcium, cadmium, chrome, copper, iron, potassium, magnesium, manganese, sodium, nickel, phosphorus, lead, strontium and zinc) were measured according to the laboratory standards through their respective characteristic optical emission spectrum.

4.3.2 Inductively coupled plasma mass spectrometry

The ICP-MS provides a measurement of metal and some non-metal concentrations, which are digested in a solution, separated and quantified through the respective characteristic ion emissions of each element in inductively coupled plasma (Ammann, 2007). The measurements were conducted at the Laboratory of Materials Science at the German Mining Museum Bochum (DBM) using a high-resolution doubly focusing mass spectrometer of Thermo according to the following procedure: If the samples did not contain lead in substantial amounts (%-level), about 100 mg sample material was digested in PTFE pressure vessels with 5 g HCl, 1.2 g HF and 5 g HNO_3 , each concentrated, for 40 minutes at 250 °C using a $\mu\text{PREP-A}$ MLS microwave. Depending on the sample type, 10 ml of H_3BO_4 (50 g/l) were added and the solution was again heated up for 20 minutes to avoid precipitation of CaF_2 , FeF_3 and/or AlF_3 . Finally, the digested samples were diluted with up to 100 ml of ultrapure water to reach a concentration of about 1000 mg/l. For the analysis of the main elements the sample solutions were diluted by 1:100, for traces 1:10 with 5% HNO_3 . The measurement was carried out with a FAST SC-system, ST 5532 PFA $\mu\text{-FLOW}$ nebulizer, a Peltier-cooled PFA spray chamber and a 1.8 mm sapphire injector in a triple detector mode at three different mass resolutions (in $m/\Delta m$) depending on the measured element. The measurements were calibrated with the certified reference materials CRM 241b (Czech Metrology Institute), FeR-1 and FeR-2 (Geological Survey of Canada) and GBW 07107.

4.3.3 Portable energy dispersive X-ray fluorescence spectrometry

The p-ED-XRF is a fast, non-consumptive, accurate and reproducible method to determine the element composition of rocks and sediments (Ramsey et al., 1995; De Vries and Vrebos, 2002; Jenkins, 1999) and has also already been applied for the measurement of bog iron ores

and iron slags (Joosten et al., 1998; Kaczorek et al., 2004). The element measurements were conducted at the laboratory of the Geographical Institute of the Freie Universität Berlin using a portable Thermo Fisher Scientific Analyticon NITON XL3t energy-dispersive XRF spectrometer equipped with a CCD-camera, a semi-conductor detector with an Ag-anode. For each measurement about 4 g of homogenized sample material was placed in plastic sample cups and sealed with 0.4 μm thick mylar film foil. The so prepared sample cups were placed on the p-ED-XRF and measured for 120 s with several filters for the detection of the specific elements. The utilized filters consist of a main filter with 50 kV, a low filter with 15/20 kV, a light filter with 8 kV and a high filter with 50 kV. The X-ray power is limited to 2 W. Calibrated measurements were conducted with internal standard material measured at the German Mining Museum Bochum (section 4.3.2) for the elements iron, silicon, manganese, calcium, phosphorus, potassium, barium and titanium. For calibration each of the internal laboratory standard samples was measured four times without calibration. The mean values were then plotted against the reference values in order to calculate a calibration function with a linear correlation coefficient as a quality measure. Outliers that distinctly impaired the coefficient were excluded from the calibration. By applying this procedure, it was possible to measure reproducible results. During the evaluation of the results a review was conducted if the measured values exceeded four times the standard deviation of the measuring error and if the highest sample measurement was not exceeded by the internal standard material. The element contents were subsequently converted to oxides using standard conversion factors based on the molar mass, whereby the iron contents of oxidized bog iron ores were converted to Fe_2O_3 and the reduced iron slags were converted to FeO . The absolute deviations from the known contents of the standard material were $\pm 0.6 \text{ mass\%}$.

4.3.4 X-ray powder diffraction

The XRD provides a fast and non-consumptive accurate and reproducible method to determine mineral concentrations in mineral compounds, such as soil samples, on the basis of the unique diffraction behavior depending on the crystal structure of each crystalline mineral towards induced X-ray emissions (Herz and Garrison, 1998). The XRD measurements were conducted at the laboratory of the Geographical Institute of the Freie Universität Berlin using a Rigaku MiniFlex 600 X-Ray Diffractometer with a copper $\text{K}\alpha$ tube and a D/tex Ultra2 detector. The sample material was pressed without regulation into sample holders and analyzed at 15 mA/40 kV ($\text{Cu } \text{K}\alpha$) from 3° to 80° (2θ) with a goniometer step velocity of 0.02° steps and $0.5^\circ/\text{min}^{-1}$. The software X'Pert HighScore Version 1.0b of Philips Analytical

B.V. was used for identification and determination of semi-quantitative mineral compositions. In the measurement procedure five preprocessing steps were applied: (i) correction of outliers; (ii) elimination of $K\alpha_2$ -emissions; (iii) calibration of quartz I = 100 main peak ($d = 3.34 \text{ \AA}$); (iv) identification of reflex peaks and (v) subtraction of background noise. In order to derive specific minerals from the reflex peaks standardized reference Powder Diffraction Files (PDF) of the ICDD (International Centre for Diffraction Data) were used. The interpretation was conducted very conservatively with only clearly detectable peaks being taken into account. Since the peak intensities of different minerals were not quantitatively comparable to each other the evaluation of mineral contents was conducted semi-quantitatively according to Schütt (2004), using four classes.

4.3.5 Magnetic susceptibility

The MS is a dimensionless value, which represents the magnetizability of a substance and in this case indicates changes in the depositional environment of the soil layers (Cardarelli, 2008). The MS of the sampled sediments was determined in closed non-magnetic plastic tubes – with a diameter of 5 cm – measured every 2 cm using a Bartington Instruments MS2C core scanning sensor system. The measurements were conducted according to the Operation Manual for MS2 Magnetic Susceptibility System (Bartington Instruments, 2008). After a settling time of more than 10 minutes a calibration check was conducted using a standard calibration core. The actual measurements were only conducted if the results of the standard calibration core were obtained within 5 % of the standard value. During the measurements measured outliers were confirmed by repeated measurements. In order to connect the MS values in a consecutive figure the occurring distinctly lower MS values at the ends of each core meter were excluded from further processing.

4.3.6 pH value and electrical conductivity

Through the pH value the acidity or basicity of an aqueous solution is expressed, which represents the H^+ -activity of this solution (Blume et al., 2011). For the pH measurements 5 g sample material was suspended in 12.5 ml of 0.1 M KCl, stirred up and left in suspension for 30 minutes. The pH values were measured using a stationary HANNA instruments HI 221 Calibration Check Microprocessor pH Meter.

The EC represents a measure to determine the conductivity of a material. In suspended soil samples it mainly represents the salinity of the respective soil sample (Blume et al., 2011). For the EC measurement 5 g sample material was suspended in 12.5 ml purified water, also

stirred up and left in suspension for 30 minutes. The EC was measured using a handheld HANNA instruments HI 98301 DiST® 1 TDS Tester. For the pH and the EC measurement each sample was measured twice and in case of identified deviations the measurement was repeated and outliers erased before the results were averaged.

4.3.7 Phosphate content

The phosphate contents were estimated semi-quantitatively by applying the phosphate spot test (Gundlach, 1961) after Feigl (1960). About 2 g of soil material were mixed with ammonium molybdate solution on filter paper for 30 s. As a reducing agent of the molybdenum subsequently ascorbic acid was added. In the following reaction the amount of phosphate in the soil sample was represented by the intensity of blue color of the resulting phosphate molybdate acid (Eidt, 1973; Gundlach, 1961). The resulting reaction was interpreted in 5 classes: I (no phosphate content), II, III, IV and V (very high phosphate content; Wallin et al., 2008).

4.3.8 Inorganic and organic carbon estimated from loss on ignition LOI550 and LOI900 and measured with Wösthoff Carmograph and LECO Analyzer

The TIC and TOC estimation from the LOI and the TIC and TC measurement from destructed TIC with acidic reactions and combusted TC in the oxygen stream and represent two methods for the derivation of TIC and TOC contents in sediment samples.

The LOI represents the weight loss during heating of soil samples between temperatures of 105 °C and 550 °C (LOI550) and 550 °C and 900 °C (LOI900; Dean, 1974; Heiri et al., 2001). From the LOI550 the TOC content of a soil sample can be estimated, while from the LOI900 the calcium carbonate (CaCO_3) and TIC content can be assessed. For the measurement approximately 1 g of sample material was added into a muffle container. With each annealing process also approximately 0.5 g pure CaCO_3 and charcoal/ CaCO_3 standard material were processed according to the same procedure. For the annealing process to 550 °C and then to 900 °C a Thermo Scientific M110 Muffle Furnace was used according to Dean (1974) and Heiri et al. (2001). In order to calculate the LOI550 and LOI900 the empty weight of the container [105 °C], the dry weight of the sample with container [105 °C] and the muffled weights [550 °C respectively 900 °C] of the samples with container were measured subsequently to a cooling to room temperatures in a desiccator. The LOI550 and LOI900 were then calculated in mass% according to the following formulas:

$$\text{LOI550} = \frac{(\text{dry weight [105 }^{\circ}\text{C]} - \text{muffled weight [550 }^{\circ}\text{C]})}{(\text{dry weight [105 }^{\circ}\text{C]} - \text{empty weight [105 }^{\circ}\text{C]})} * 100$$

$$\text{LOI900} = \frac{(\text{muffled weight [550 }^{\circ}\text{C]} - \text{muffled weight [900 }^{\circ}\text{C]})}{(\text{dry weight [105 }^{\circ}\text{C]} - \text{empty weight [105 }^{\circ}\text{C]})} * 100$$

Data: Dean (1974); Heiri et al. (2001); Ad-Hoc-AG Boden (2005) and Blume et al. (2010).

A successful measurement was given, if the expected organic and CaCO_3 contents were calculated correctly for the standard material. From the LOI550, which is approximately equivalent to the soil organic matter (SOM) content (Blume et al., 2010), the TOC was estimated with an approximate empiric factor of 1/1.72 for sediment samples and 1/2.00 for peat samples (Ad-Hoc-AG Boden, 2005). From the LOI900 the CaCO_3 content was estimated with a conversion factor of 1/0.44 (Dean, 1974). From the estimated CaCO_3 content the TIC was calculated with a conversion factor of 0.12 (Bertrand et al., 2012; Dean, 2009). The absolute deviations from the known contents of the standard material were ± 1.0 mass% TOC and ± 0.9 mass% TIC for sediment samples as well as ± 2.2 mass% TOC and ± 1.5 mass% TIC for bog iron ore and slag samples.

The TIC measurements were conducted using a Wösthoff Carmograph C 16 Carbon Analyzer according to Blättermann et al. (2012) with 100 mg sample material for each sample in a reaction with 42.5 % phosphoric acid by measuring the produced CO_2 content. The TC measurements were conducted using a LECO TruSpec CHN + S-Add-On Elemental analyzer with 100 mg sample material for each sample prepared in tin foil and combusted in a pure oxygen stream also by measuring the produced CO_2 content. These measurements were conducted according to the operational manual and laboratory standards, using standard material with 12.0 (CaCO_3), 4.2, 2.4 and 0.8 mass% TIC. The TOC was calculated from the difference between TC and TIC according to Schneider et al., (2015). From the TIC and TOC the CaCO_3 and SOM contents were calculated according to the above mentioned conversion factors. The absolute deviations from the known contents of the standard material were ± 1.5 mass% TIC and ± 0.4 mass% TC.

4.3.9 Particle size analysis with laser diffraction

This method of particle size analysis is based on the different scattering of light at sediment particles of different size (Beuselinck et al., 1998). Depending on the estimated particle size of the samples 0.2 to 1.5 g of each sample was suspended in 3 ml 0.1 M sodium

pyrophosphate and intermixed for 12 hours in an overhead shaker. The particle size analysis was conducted with a Particle Size Analyzer of Beckmann Coulter according to the laboratory standards.

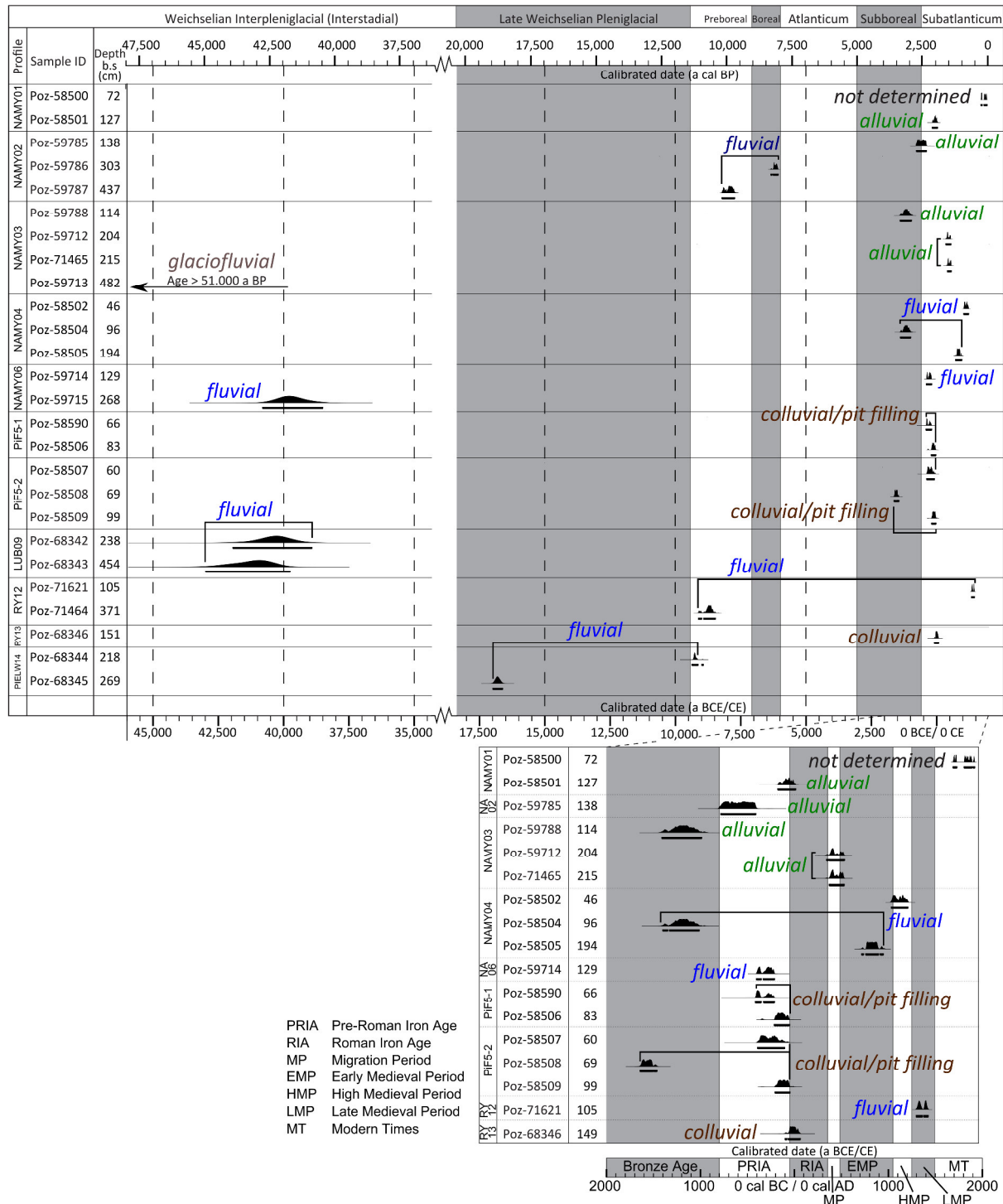


Fig. 13: Radiocarbon dates including chronological interpretation.

Data: ¹⁴C-datings conducted at the Poznan Radiocarbon Laboratory, Poland in 2014/2015, calibration with Calib Rev 7.0.1., calibration curve IntCal13 after Stuiver and Reimer (1993) and Reimer et al. (2013), Holocene chronology Walanus and Nalepka (2005) and Starkel et al. (2006), Pleistocene chronology Marks (2012), Börner (2007), Krzywicki (2002), Wysota et al. (2000), pre- and historical chronology Kümmel (2009), Haberstroh (2000), Goetz (2003), Borgolte (2002), North (2007) and sedimentological facies from Ad-Hoc-AG Boden (2005).

4.3.10 Dating

Absolute ages were measured by accelerator mass spectrometry ^{14}C -dating, deriving the age from the $^{14}\text{C}/^{12}\text{C}$ ratio of sampled charcoal fragments, macroplant remains and bulk samples (Bradley, 1999), at the Poznan Radiocarbon Laboratory, Poland (Fig. 13; Appendix A, Table A.3). Prior to the measurements the available dating material was isolated from sediment material. Alleged charcoal fragments were investigated under the optical microscope in order to avoid an accidental sampling of manganese concretions. The results of case study I (section 5.1), were calibrated with Calib Rev 7.0.1, applying the calibration curve IntCal13 (Reimer et al., 2013), whereas the results of case study III (section 5.3), were calibrated with OxCal 4.2 (Bronk Ramsey and Lee, 2013), also applying the calibration curve IntCal13 (Reimer et al., 2013). The chronological interpretation of the ^{14}C -dates was conducted according to further literature (Fig. 13).

4.4 Secondary and primary data analyses and spatial visualizations

The statistical analyses were conducted using the Microsoft Excel tools StatistiXL and Real Statistics. The spatial data analyses and visualizations of secondary spatial information and primary results in the study area was conducted with ArcGIS 10.0-10.3, GrassGIS 6.4.4-7.0 and QuantumGIS 1.8.0-2.12.3. Additionally to the primary results produced during the field and laboratory analyses the following secondary map material and data sets were taken into account for the production of map material and visualization of the results:

Digital elevation models

- 3-arc second SRTM-data from Reuter et al. (2007)
- 1-arc second SRTM-data from USGS (2000)
- 1 m horizontal resolution LiDAR-data from CODGiK (2013)

Topographical maps

- Topographical detailed maps 1 : 25 000 from TK25 (1886-1938)
- Topographical detailed maps 1 : 50 000 from TK50 (1992)

Geological maps

- General glacial map 1 : 1000 0000 from Liedtke (1981)
- Geological detailed maps 1 : 50 000 from Bartczak (1997) and Cinio (1997)
- General geological map without Cainozoic deposits 1 : 1000 000 from Dadlez et al. (2000)

Further thematic maps

- General soil map 1 : 300 000 from Pawlak (1997), map sheet 28
- General potential vegetation map 1 : 300 000 from Pawlak (1997), map sheet 52

Secondary spatial data

- Country borders and rivers from Natural Earth Data (2013)
- Water surfaces from KZGW (2015)
- Slag and settlement sites from AZP (since 1978)
- Currently forested areas from Geofabrik (2015)

5. Case studies

5.1 Case study I:

Iron, Humans and Landscape – Insights from a Micro-Region in the Widawa Catchment Area, Silesia

Michael Thelemann^{a,c,*}, Enrico Lehnhardt^{b,c}, Wiebke Bebermeier^{a,c}, Michael Meyer^{b,c}

^aFreie Universität Berlin, Institute of Geographical Sciences, Malteserstraße 74-100, 12249 Berlin, Germany

^bFreie Universität Berlin, Institute of Prehistoric Archaeology, Fabeckstraße 23-25, 14195 Berlin, Germany

^cTOPOI Excellence Cluster, Hittorfstraße 18, 14195 Berlin, Germany

*Corresponding author: E-Mail: michael.thelemann@fu-berlin.de

published in 2016 in

Special Volume 4 (2015) of eTopoi. Journal for Ancient Studies:

Wiebke Bebermeier, Daniel Knitter and Oliver Nakoinz (Eds.). „*Bridging the Gap – Integrated Approaches in Landscape Archaeology*”, Berlin: Exzellenzcluster 264 Topoi.

Keywords: Bog iron ore, early iron smelting, formation, human-environmental interactions, landscape archaeology, pre-Roman Iron Age, Przeworsk culture (7)

Abstract

The Widawa catchment area is located in Northeastern Silesia, Poland, and belonged to the southwestern distribution area of the Przeworsk culture from the younger pre-Roman period until the younger Roman period. It is estimated that iron smelting was introduced to this area with the emergence of the Przeworsk culture, circa the 2nd century BCE. Certain cultural and environmental requirements must have been met in order for this technology to spread to this area. Within the framework of interdisciplinary research, the archaeological context of an archaeological site as well as the natural archives were investigated to explore the preconditions and to describe the beginning of early iron smelting in this region.

The original publication is accessible at:

<http://edition-topoi.org/articles/details/iron-humans-and-landscape-insights-from-a-micro-region-in-the-widawa-catchm>

If access is not available, please contact: michael.thelemann@fu-berlin.de

5.2 Case study II:

Bog iron ore as a resource for prehistoric iron production in Central Europe – A case study of the Widawa catchment area in eastern Silesia, Poland

Michael Thelemann^{a,c*}, Wiebke Bebermeier^{a,c}, Philipp Hoelzmann^{a,c}, Enrico Lehnhardt^{b,c}

^aFreie Universität Berlin, Institute of Geographical Sciences, Malteserstraße 74-100, 12249 Berlin, Germany

^bFreie Universität Berlin, Institute of Prehistoric Archaeology, Fabeckstraße 23-25, 14195 Berlin, Germany

^cTOPOI Excellence Cluster, Hittorfstraße 18, 14195 Berlin, Germany

*Corresponding author: E-Mail: michael.thelemann@fu-berlin.de

in press (2016) in

Special Issue of Catena:

Sjoerd Kluiving, Vanessa Heyvaert, Andy Howard, Wiebke Bebermeier (Eds.).

“Geoarchaeology: Human-environment interactions in the Pleistocene and Holocene”,
Elsevier B.V.

Keywords: Bog iron ore, Prehistoric iron smelting, Geochemical fingerprinting, Prehistoric iron slags, portable ED-XRF, Przeworsk culture (6)

Abstract

Spreading from the Near East in the declining Bronze Age from the 2nd millennium BCE onwards, the technique of iron smelting reached Eastern Silesia, Poland, in approximately the 2nd century BCE (pre-Roman Iron Age). At this time the region of the Widawa catchment area was inhabited by the Przeworsk culture. While the older moraine landscape of the study area lacks ores from geological rock formations, bog iron ores were relatively widespread and, due to their comparatively easy accessibility, were commonly exploited for early iron production. This paper investigates the mineralogical and elemental composition of local bog iron ore deposits and iron slag finds, as a by-product of the smelting process, also taking into account the state of the art in research regarding the formation, distribution and utilization of bog iron ores and considering data from comparative studies.

The crystalline mineralogical composition of local bog iron ores is dominated by quartz (SiO_2) and goethite ($\alpha\text{-FeO(OH)}$), in contrast to slag samples in which fayalite (Fe_2SiO_4), wüstite (FeO) and quartz, with traces of goethite, represent the main minerals. Ores and slags are both characterized by notable hematite (Fe_2O_3), magnetite (Fe_3O_4) and maghemite ($\gamma\text{-Fe}_2\text{O}_3$) contents. Analyzed bog iron ore samples show iron contents of up to 64.9 mass% Fe_2O_3 (equivalent to 45.4 mass% Fe), whereas the iron contents of bloomery slags vary between 48.7 and 72.0 mass% FeO (equivalent to 37.9 and 56.0 mass% Fe). A principal component analysis of the element contents, which were quantified by portable energy-dispersive X-ray fluorescence spectrometry, indicates local variations in the elemental composition. The results of this study show that bog iron ores are relatively widely distributed with spatially varying iron contents along the Widawa floodplain but present-day formation conditions, such as changed groundwater levels, are negatively affected by modern land-use practices, such as agriculture and melioration measures.

The original publication is accessible at:

<http://www.sciencedirect.com/science/article/pii/S0341816216301321>

If access is not available, please contact: michael.thelemann@fu-berlin.de

5.3 Case study III:
Landscape history since the Saalian Drenhte stadial in the Widawa
Catchment Area in Silesia, Poland:
A case study on long-term landscape changes

Michael Thelemann^{a*}, Wiebke Bebermeier^a, Philipp Hoelzmann^a, Brigitta Schütt^a

^aFreie Universität Berlin, Institute of Geographical Sciences, Malteserstraße 74-100, 12249 Berlin, Germany

*Corresponding author: E-Mail: michael.thelemann@fu-berlin.de

resubmitted in

Thematic Volume of Quaternary International:

Rolfe Mandel, Kathleen Nicoll (Eds.).

*“Topics in Geoarchaeology: Reconstructions of Ancient Landscapes and
Paleoenvironments”*, Elsevier B.V.

Keywords: Holistic landscape Reconstruction, Geoarchaeology, Pleistocene, Human-Environment Interactions, Early Iron Smelting, Przeworsk Culture (6)

Abstract

With the pre-Roman Iron Age, approximately in the 2nd century BCE, a cluster of iron smelting sites began to develop in the catchment area of the Widawa River, located in the Old Drift landscape of northeastern Silesia, Poland. Before this area became an important local center for early iron smelting during the late pre-Roman Iron Age to the Roman period, its landscape had undergone distinct changes since it was covered for the last time by ice sheets during the Saalian Drenthe stadial. Besides climate driven environmental and landscape changes during the late Pleistocene and Holocene the area is influenced by a settlement history since the Mesolithic.

In order to understand the holistic development of this pre-Roman Iron Age iron smelting cluster this paper investigates the late Pleistocene landscape history of the southeastern part of the Widawa catchment with a focus on study sites in the context of early human impacts. Therefore a multi-proxy approach was applied, integrating geomorphological mappings and sedimentological analyses (lithology, particle grain size, bulk parameters, total inorganic and

organic carbon) of selected drilling transects, dated by AMS radiocarbon with archaeological records, geological and topographical data.

The study area developed its present shape in six main phases: Subsequently to the last ice coverage (A), which extensively accumulated Saalian glacial till, the Widawa valley initially developed its present directionality (B). The subsequent valley formation is characterized by a succession of accumulation phases of glaciofluvial deposits of the Drenthe (C) and Warthe stadial (D) and fluvial deposits of the Weichselian glacial period (E) and the Holocene (F), which each were followed by a subsequent incision of the Widawa valley. First human impacts on the sediment budget are represented by alluvial fan deposits, which accumulated at the end of the 4th millennium BP. This alluvial fan, situated in the context of three prehistoric slag sites, shows a complex sedimentological succession of charcoal dated fan sediments that indicate a human impact on the landscape development during the pre-Roman Iron Age and the Roman period, pointing to a temporal and spatial context of early iron smelting.

The original publication is currently in review for:

<http://www.sciencedirect.com/science/journal/10406182>

If access will not be available, please contact: michael.thelemann@fu-berlin.de

1. Introduction

From the pre-Roman Iron Age (PRIA) northeastern Silesia, Poland, was inhabited by the Przeworsk culture (Godłowski, 1985). Their settlement and smelting sites were frequently situated at the floodplain margins of the Oder River and its tributaries (Orzechowski, 2002). According to the database of the Archaeological Record Poland (AZP, since 1978), a very particular cluster of early iron smelting sites of this culture, representing the investigated study area, is located in the vicinity of the modern town of Namysłów, along the floodplain of the Widawa River. The material culture of these sites comprises remarkable findings: artefacts like bog iron ore fragments, iron slags and furnace remains point to an early smelting and processing of iron (Thelemann et al., 2016). As Joosten et al. (1998) documented for the Netherlands, early iron production from the 2nd century CE resulted in an increasing demand for charcoal and – depending on the magnitude of the smelting activities – this led to largely deforested areas. Depending on the intensity of deforestation, mining induced erosional and depositional events, which might have influenced the landscape development (James et al., 2013). On the regional scale of Silesia those increased human impacts without iron smelting context are shown for the Bronze Age and the Iron Age (Pawłowski et al., 2014; Zygmunt, 2009).

Table 1: Pleistocene and Holocene North West European and Polish chronology.

Series		Stages and periods	Marine Isotope Stages	approx. age
		North West European nomenclature	[MIS]	[in ka BP]
Holocene [Byt-Semander Sequence]###	Subatlantic##	Subatlantyck##	1#	2.5-0.0##
	Subboreal##	Subboreal##	1#	5.0-2.5##
	Atlantic##	Atlantyck##	1#	8.0-5.0##
	Boreal##	Boreal##	1#	9.0-8.0##
	Preboreal##	Preboreal##	1#	11.7-9.0##
Pleistocene	Weichselian glaciation*	Zlodowacenie Wisły [Vistulian glaciation/northern Polish glaciation]**	5d-1#	110-11.7#
	Eemian interglacial*	Interglacjał eemski [Eemian interglacial]**	5e*	130-110#
	Warthe stadial, Saalian complex*	Zlodowacenie Warty [Warty stadial, middle Polish glaciation]**	6*	220-170*
	Seyda interval*	Kamienna-interstadial*	6*	220*
	Drenthe stadial, Saalian complex*	Zlodowacenie Odry [Oder stadial, middle Polish glaciation]**	6*	290-220*
	Holsteinian interglacial*	Interglacjał mazowiecki [Mazovian interglacial]**	11*	360*
	Elsterian glaciation*	Zlodowacenie Sanu [Sanian glaciation/southern Polish glaciation]**	12*	510-470*

*Cohen & Gibbard (2011); Gozhik et al. (2012); Börner (2007) **Bartczak (1997); Cincio (1997); Börner (2007); Lindner & Marks (2008)
#Marks et al. (in press); Engels et al. (2010) ##Borówka et al. (2004); Walanus & Nalepka (2005) ###Starkel (1995)

Using a geoarchaeological approach, selected sediment archives located in the vicinity of pre-Roman Iron Age sites were investigated in order to analyze whether the introduction of iron smelting was associated with additional pressure on the landscape. To understand the holistic long-term landscape development dynamics of the study area this geoarchaeological approach also focuses on investigations of landscape development as a whole since the last direct ice coverage during the Saalian Drenthe stadial to the late-Holocene (Table 1). Although this

region has been geologically, palynologically and historically investigated (Bartczak, 1997; Cincio, 1997; Kuszell et al., 2007; Bykowski, 1997), there has been no such comprehensive study of the landscape history. The paper thus deals with the following research questions: (i) When and how did the Widawa valley develop and establish its present shape and (ii) are there early human impacts detectable in the sediment archives of the study area and can these be set in the context of early iron smelting?

2. Regional setting

The study area is situated in the Oleśnica Plain in the catchment area of the Widawa River, a tributary of the Oder River in northeastern Silesia, Poland (Fig. 1A). To the north (Fig. 1B) the catchment area is delimited by the Trzebnica Ridge (Wał Trzebnicki; Winnicki, 1997; Rössner, 1998; Kuszell et al., 2007), a terminal moraine of the Warthe stadial deposited during the Saalian complex (Table 1; Rössner, 1998; Liedtke, 1981, Litt et al., 2007). The Oder glacial valley of the Warthe stadial forms the southern boundary of the catchment area (Fig. 1B).

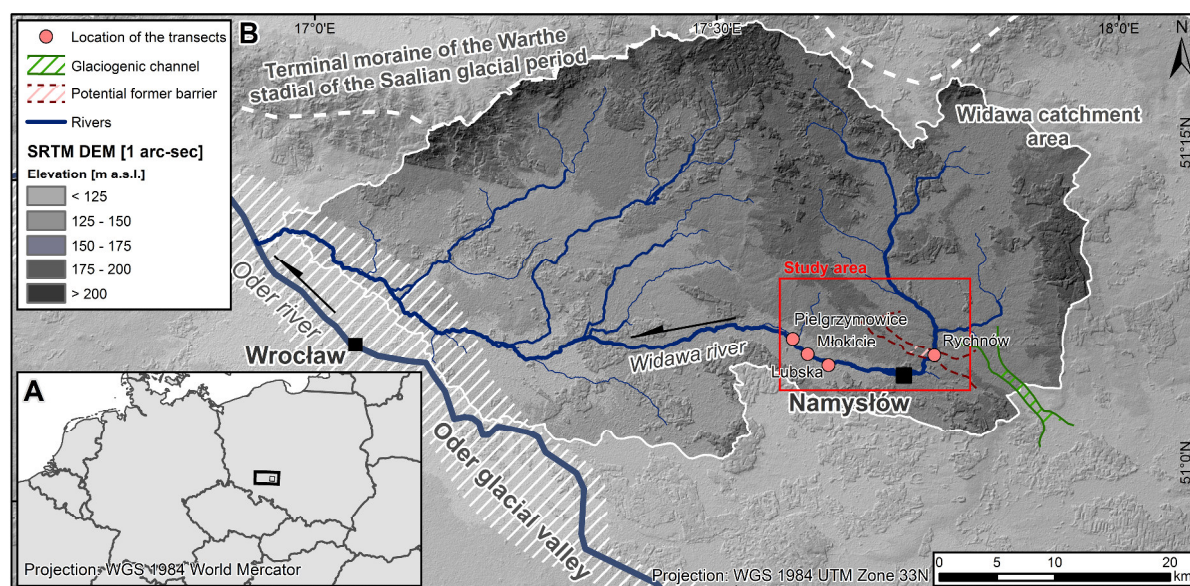


Fig. 1: A: Location of the study area in Silesia, Poland; B: Study sites in the Widawa catchment area.

Data: Fig. 1: A: Country borders from Natural Earth Data (2013); B: Digital elevation model, Widawa catchment area and hillshade (z-factor 3) from one arc-sec SRTM-data from USGS (2000) with a horizontal resolution of 30 m; rivers from KZGW (2015); terminal moraine, Oder glacial valley and (sub)glacial channel from Liedtke (1981).

Our focus is on a cluster of prehistoric slag sites recorded by the archaeological records (AZP, since 1978). These sites are situated along the Widawa floodplain and concentrate around the Michalice Reservoir (Fig. 2), which was dammed in 2001 (Wiatkowski et al., 2010). The topography of the study area varies between 137 and 187 m above sea level (a.s.l.) and is

characterized by flat landforms with hillslopes mostly below 1° , particularly rarely exceeding 5° inclination. Steeper natural slopes only occur at former undercut banks at the margins of the Widawa floodplain, but never exceed 20° . The majority of slopes are exposed towards south and north (CODGiK, 2013). On topographic maps from the late 19th century, the upper reaches of the Widawa are represented by an anastomosing river system, and the lower reaches are characterized by alternating meandering and anastomosing sections. Some parts of the Widawa show straight courses and have been subject to hydraulic engineering measures (TK25, 1886-1938). Today the river course is almost entirely regulated.

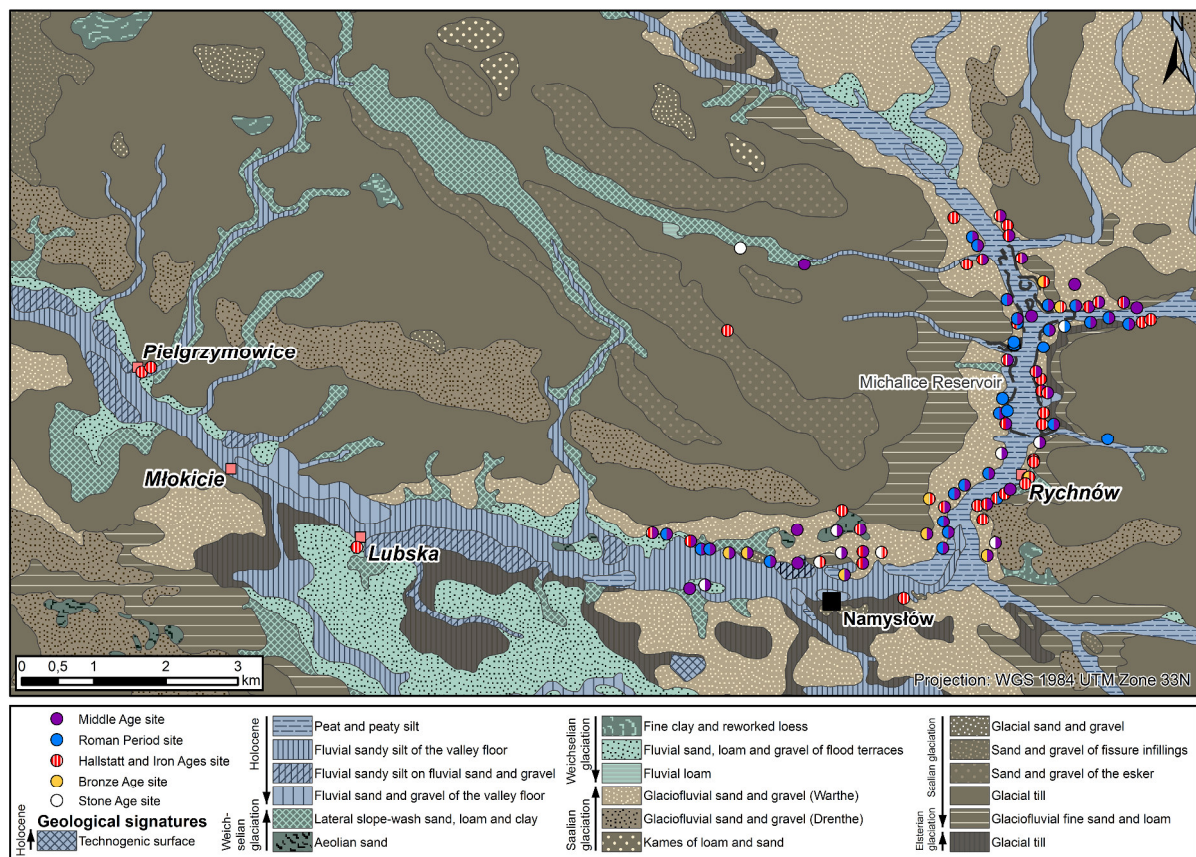


Fig. 2: Quaternary deposits with study sites and known archaeological sites since the Stone Age.

Data: Quaternary deposits from Geological detailed map 1 : 50.000 from Bartczak (1997), map sheet 0766; Cincio (1997), map sheet 0767; Archaeological sites from AZP (since 1978) and Bykowski (1997); Current location of the Michalice Reservoir from CODGiK LiDAR data (2013).

In the European context the climate of the study area is characterized by a rather cold temperate, all-year humid continental climate with warm summers (Przybylak et al., 2010; Köppen, 1931 after Kuttler, 2009; Climate-data.org, 1982-2012). Monthly temperatures average between -2 and 18°C and annual precipitation totals between 500 and 600 mm (Pelzer, 1991; Rössner, 1998; Climate-data.org, 1982-2012).

Geologically, the Widawa catchment area belongs to the Pleistocene Old Drift landscape (Liedtke, 1981) with Quaternary deposits reaching a thickness of up to 90 m (Bartczak, 1997).

The oldest geological surface deposits are represented by glacial till of the Elsterian glacial period (Table 1), exposed especially along the Widawa floodplain in the lower parts in the south but also in the north and east of the study area (Fig. 2). These Elsterian glacial tills reach a thickness of up to 35 m in the northwestern plateaus (Bartczak, 1997). Most of the plateaus are covered by glacial till, sand and gravel of eskers deposited during the Drenthe stadial of the Saalian complex and reaching up to 13 m thickness (Fig. 2). The upper slopes are formed in glaciofluvial sand and gravel of the Drenthe stadial, while the lower slopes are often covered by glaciofluvial deposits of the Warthe stadial, followed by fluvial and lateral slope-wash deposits (translated according to Kittel et al. (2014) from the Polish term '*deluvial*') accumulated during the Weichselian glacial period (Table 1). The lowlands of the Widawa floodplain and its tributaries are covered by Holocene fluvial deposits (Fig. 2).

Apart from a general analysis of the study area the focus of this case study is on the sites of Rychnów, Lubska, Młokicie and Pielgrzymowice, situated along the floodplain of the Widawa River (Fig. 1B). The Rychnów site is regarded as key because sedimentological record shows the most complete sequence of Pleistocene and Holocene deposits. According to the AZP, Rychnów, Lubska and Pielgrzymowice are classified as PRIA slag sites (AZP, since 1978).

3. Material and methods

In 2013 and 2014, two field campaigns conducted geomorphological mapping after Leser and Stäblein (1985), and collected 16 percussion drillings along the Widawa floodplain (Appendix, Table A1). From east to west, percussion drillings were arranged in transects at the Rychnów, Lubska, Młokicie and Pielgrzymowice sites, respectively (Fig. 2). These drillings used a Wacker drilling hammer (BHF 30 S) with a 5 cm core diameter in an open or closed driving core drilling system. All geographical coordinates were determined by handheld GPS device. The vertical position in m a.s.l. and the topography of the transects were derived from CODGiK LiDAR data (CODGiK, 2013) with a vertical resolution of 0.15 m (Appendix, Table A1).

Sediment cores were macroscopically described recording grain size and lithology, carbonate and organic content, moisture, texture, rooting, hydromorphic and special features (e.g. charcoal, macroplant remains, shell or ceramic fragments, etc.) to the standards of the German Pedological Mapping Guide (Ad-Hoc-AG Boden, 2005). Soil color was determined using the Munsell soil color chart (Munsell, 2000). Altogether 19 AMS radiocarbon (^{14}C)

dates from 11 drillings were analyzed at the Poznan radiocarbon laboratory, Poland (Table 2). The calibration was conducted with OxCal 4.2 (Bronk Ramsey and Lee, 2013) applying the calibration curve IntCal13 after Reimer et al. (2013). For the drillings of transect Rychnów I (drilling profiles RYCHNOW12, NAMY02, NAMY03 and NAMY07) the magnetic susceptibility (MS), the loss on ignition (LOI), the total inorganic (TIC) and organic carbon (TOC) contents, the pH value and the electric conductivity (EC) were determined. Profile NAMY01 was not analyzed in the laboratory as it represents a parallel drilling of profile NAMY02. The MS was measured for each closed core meter in 2 cm steps using a Bartington MS2C. Subsequently, the sampling was conducted according to the stratigraphy.

The LOI was measured according to Dean (1974) and Heiri et al. (2001) at 550 and 900 °C using a Thermo Scientific M110 Muffle Furnace. To estimate the TOC from the LOI at 550 °C the factor of $1 \cdot 1.72^{-1}$ was applied (Blume et al., 2010). To estimate the CaCO_3 content from the LOI between 550 and 900 °C the factor of $1 \cdot 0.44^{-1}$ was used (Dean, 1974), and to convert the CaCO_3 content to TIC the factor of $1 \cdot 0.12$ was applied (Bertrand et al., 2012; Dean, 2009). Additionally, for selected samples, the total carbon (TC) was measured using a LECO TruSpec CHN + S-Add-On Elemental analyzer and the TIC was measured using a Wösthoff Carmograph C-16 Carbon Analyzer (according to Blättermann et al., 2012). The TOC was calculated from the difference between TC and TIC (Schneider et al., 2015) and converted to soil organic matter (SOM) applying the empirical conversion factor of 1.72 for sediment and 2.00 for peats (Ad-Hoc-AG Boden, 2005). The pH values were measured using a stationary HANNA instruments HI 221 Calibration Check Microprocessor pH Meter in a suspension of 12.5 ml of 0.1 M KCl with 5 g sample material. The EC was measured using a handheld HANNA instruments HI 98301 DiST® 1 TDS Tester in a suspension of 12.5 ml purified water with 5 g sample material. For selected samples at the study site of Lubska, the distribution of particle grain sizes smaller 1.5 mm was determined using a LS 13320 PIDS Beckmann Coulter Laser particle size analyzer measuring a suspension of 3 ml 0.1 M sodium pyrophosphate with 0.1 to 1.5 g sample material. For a geomorphological and sedimentological interpretation of the vicinity of the drilling sites and a reconstruction of surface models of different periods, the present CODGiK (2013) LiDAR DEM was combined with the geological map 1 : 50.000 (Bartczak, 1997, map sheet 0766; Cincio, 1997, map sheet 0767) with a focus on the terrace levels and the sedimentological records.

Table 2: AMS radiocarbon dates.

No	Sample ID	Drilling ID	Location [transect]	Type [carbon reservoir]	Sampling depth [cm b.s.]	Uncalibrated age* [a BP]	Calibrated age** [cal. ka BP, 2 σ]
1	Poz-58500	NAMY01	Rychnów I	Charcoal fragment	72	109.01 \pm 0.31	0.14 \pm 0.11
2	Poz-58501	NAMY01	Rychnów I	Charcoal fragment	127	2,050 \pm 30	2.11 \pm 0.09
3	Poz-59785	NAMY02	Rychnów I	Charcoal fragment	138	2,450 \pm 70	2.54 \pm 0.18
4	Poz-59786	NAMY02	Rychnów I	Macroplant remains	303	7,330 \pm 40	8.15 \pm 0.13
5	Poz-59787	NAMY02	Rychnów I	Macroplant remains	437	8,820 \pm 50	9.92 \pm 0.24
6	Poz-59788	NAMY03	Rychnów I	Charcoal fragment	114	2,960 \pm 70	3.14 \pm 0.21
7	Poz-59713	NAMY03	Rychnów I	Charcoal fragment	482	> 51,000	> 51.0
8	Poz-58502	NAMY04	Młokicie	Charcoal fragment	46	900 \pm 30	0.82 \pm 0.09
9	Poz-58504	NAMY04	Młokicie	Charcoal fragment	96	1,185 \pm 30	1.11 \pm 0.11
10	Poz-58505	NAMY04	Młokicie	Charcoal fragment	194	2,960 \pm 60	3.14 \pm 0.19
11	Poz-59714	NAMY06	Młokicie	Macroplant remains	129	2,245 \pm 30	2.55 \pm 0.09
12	Poz-59715	NAMY06	Młokicie	Charcoal fragment	268	37,200 \pm 700	41.49 \pm 1.15
13	Poz-68342	LUBSKA09	Lubska	Bulk sample (organic)	238	38,000 \pm 900	42.10 \pm 1.46
14	Poz-68343	LUBSKA09	Lubska	Macroplant remains	454	39,000 \pm 1,000	43.06 \pm 1.55
15	Poz-71621	RYCHNOW12	Rychnów I	Bulk sample (organic)	105	565 \pm 30	0.58 \pm 0.06
16	Poz-71464	RYCHNOW12	Rychnów I	Macroplant remains	371	9,420 \pm 80	10.75 \pm 0.33
17	Poz-68346	RYCHNOW13	Rychnów II	Charcoal fragment	149	2,005 \pm 30	1.96 \pm 0.08
18	Poz-68344	PIELW14	Pielgrzymowice	Macroplant remains	218	9,770 \pm 60	11.09 \pm 0.21
19	Poz-68345	PIELW14	Pielgrzymowice	Macroplant remains	269	15,480 \pm 180	18.74 \pm 0.18

*measured at the Poznan Radiocarbon Laboratory, Poland.

**calibration with OxCal 4.2 (Bronk Ramsey and Lee, 2013), calibration curve IntCal13 after Reimer et al. (2013).

4. Results and discussion

4.1 Radiocarbon datings

The 19 calibrated stratigraphically consistent ^{14}C -dates vary between 0.14 and more than 51.0 ka BP (Table 2). The oldest age was determined for the Rychnów site, which was out of ^{14}C -dating range, followed by three dates from the Młokicie and Lubska sites with dates between 41.5 and 43.0 ka BP. At the Rychnów site another three dates are clustered to dates between 8.2 and 10.8 ka BP. With a total of six dates the majority of ^{14}C -dates obtained from the sediment records are concentrated in the period between 2.0 and 3.1 ka BP (Table 2; Fig. 3).

4.2 Drilling transects

In the following paragraphs the sediment succession of the drilling transects is presented, discussed and interpreted. The complete field data records are presented in the appendix (Appendix, section A1).

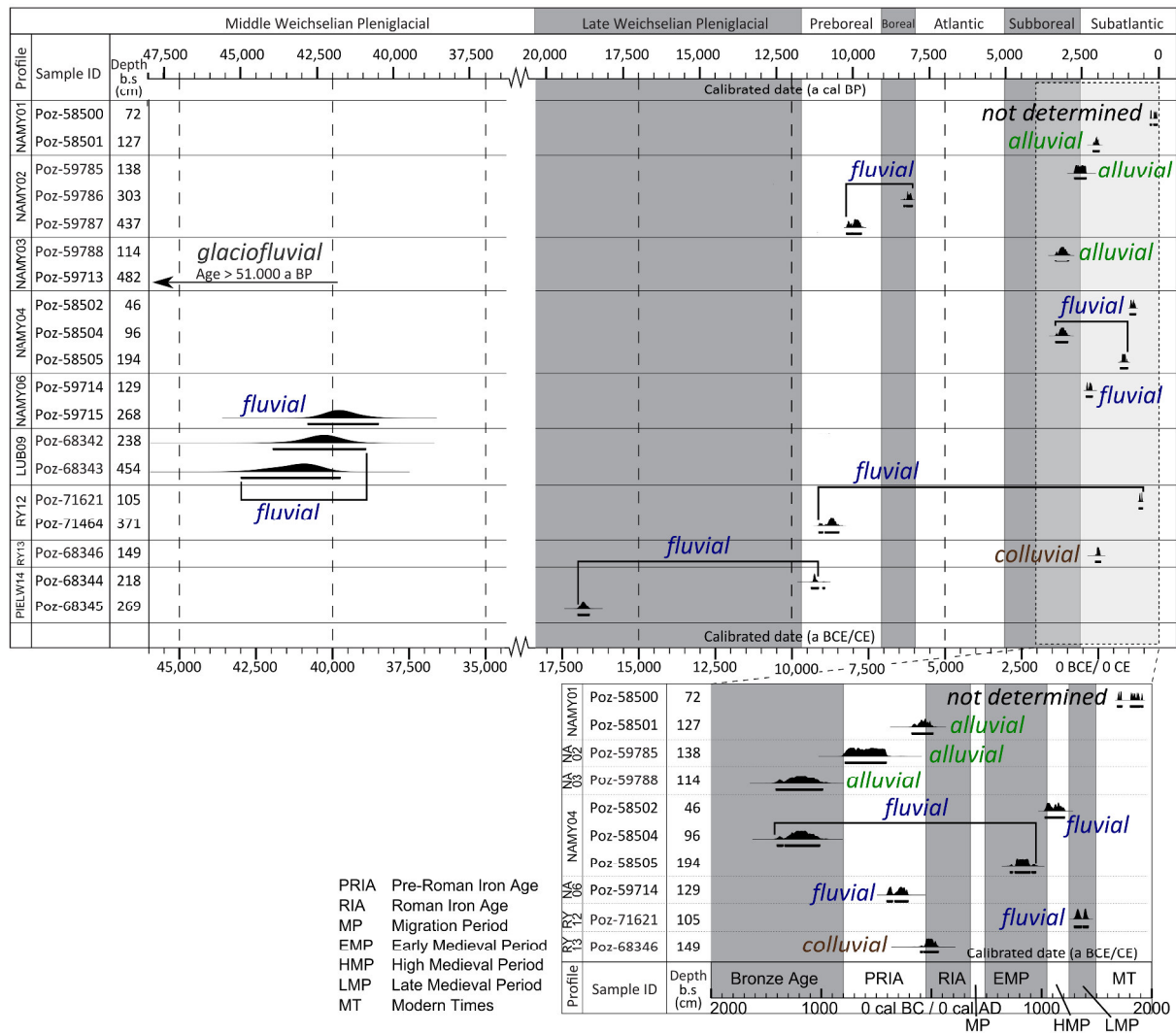


Fig. 3: Chronological overview and integration of the ¹⁴C-datings of the study area.

Data: ¹⁴C-dates conducted at the Poznan Radiocarbon Laboratory, Poland; calibration conducted with OxCal 4.2 (Bronk Ramsey and Lee, 2013), calibration curve IntCal13 after Reimer et al. (2013), ages given in a confidence range of 2σ; Pleistocene chronology according to Marks et al. (2015), Marks (2012), Börner (2007), Krzywicki (2002) and Wysota et al. (2000); Holocene chronology according to Walanus and Nalepka (2005), Starkel (1995) and Starkel et al. (2006); pre- and historical chronology according to Kümmel (2009), Haberstroh (2000), Goetz (2003), Borgolte (2002) and North (2007); sedimentological facies according to Ad-Hoc-AG Boden (2005).

4.2.1 Study site of Rychnów

The study site of Rychnów is situated in the south of the Michalice Reservoir (Fig. 4A), downslope of three prehistoric iron slag sites (Fig. 4B). The parent material of the site is characterized by Saalian glacial till (Drenthe) on the plateaus (Fig. 2), cropping out Saalian glaciofluvial fine sands and loams (Early Drenthe), Saalian glaciofluvial sand and gravel terraces (Warthe), lateral Weichselian slope-wash sand, loam and clay along the tributary and Holocene peats and peaty silts along the Widawa floodplain (Fig. 4B). Two drilling transects were conducted. The southern transect Rychnów I includes five drillings (profiles RYCHNOW12, NAMY01, NAMY02, NAMY03 and NAMY07) covering an alluvial fan at the outlet of a lateral tributary to the Widawa floodplain. The northern transect Rychnów II

was conducted on two different Pleistocene terrace levels at 2 to 4 m above the current floodplain level and consists of two profiles, RYCHNOW13 and RYCHNOW17 (Fig. 4B).

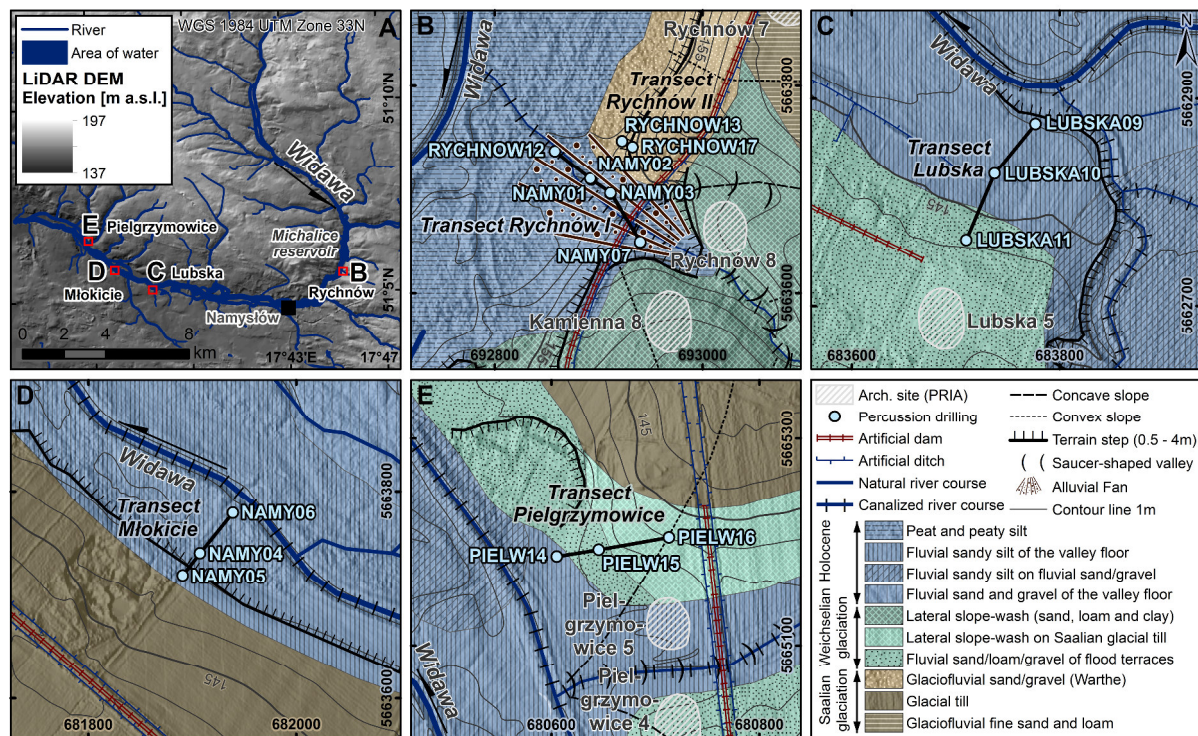


Fig. 4: Overview (A) of the geological and geomorphological setting of Rychnów (B), Lubaska (C), Młokicie (D) and Pielgrzymowice (E).

Data: 4.A.: Digital elevation model and hillshade (z-factor 3) derived from downscaled 10 m horizontal resolution LiDAR-data from CODGiK (2013); rivers from TK25 (1886-1938); lakes and reservoirs from CODGiK (2013); 4.B./C./D./E.: Quaternary deposits from Geological detailed map 1 : 50.000 from Bartczak (1997), map sheet 0766; Cincio (1997), map sheet 0767, corrected according to the results from the drilling campaign; rivers from TK25 (1886-1938), 1 : 25.000; hillshade (z-factor 3) derived from 1 m horizontal resolution LiDAR-data from CODGiK (2013); archaeological sites AZP (since 1978) and Thelemann et al. (2016).

Sediments exposed along transect Rychnów I show a succession of Elsterian to late-Holocene deposits of sandy, silty, clayey and loamy sediments with varying organic and inorganic carbon contents as well as Holocene peat layers (Fig. 5). The 6 m deep profile RYCHNOW12 is characterized by a mostly calcareous succession of loams, sands, peats and gyttja with very strong organic content and a sand layer at the top (Fig. 5). The neighboring 3 m deep profile NAMY01 is characterized by a peat layer at the base and an overlying alternating sequence of loams and sands. The parallel 5 m deep profile of NAMY02 shows a succession of sand, peat, sandy loam, loam and sand at the top. The 5 m deep profile NAMY03 is characterized by a series of loam, sand and clay, overlain by sand layers with sandy loam at the top. The 4 m deep profile NAMY07 is characterized by a succession of sandy loam, clay and a thick sequence of sand layers with sandy loam at the top (Fig. 5).

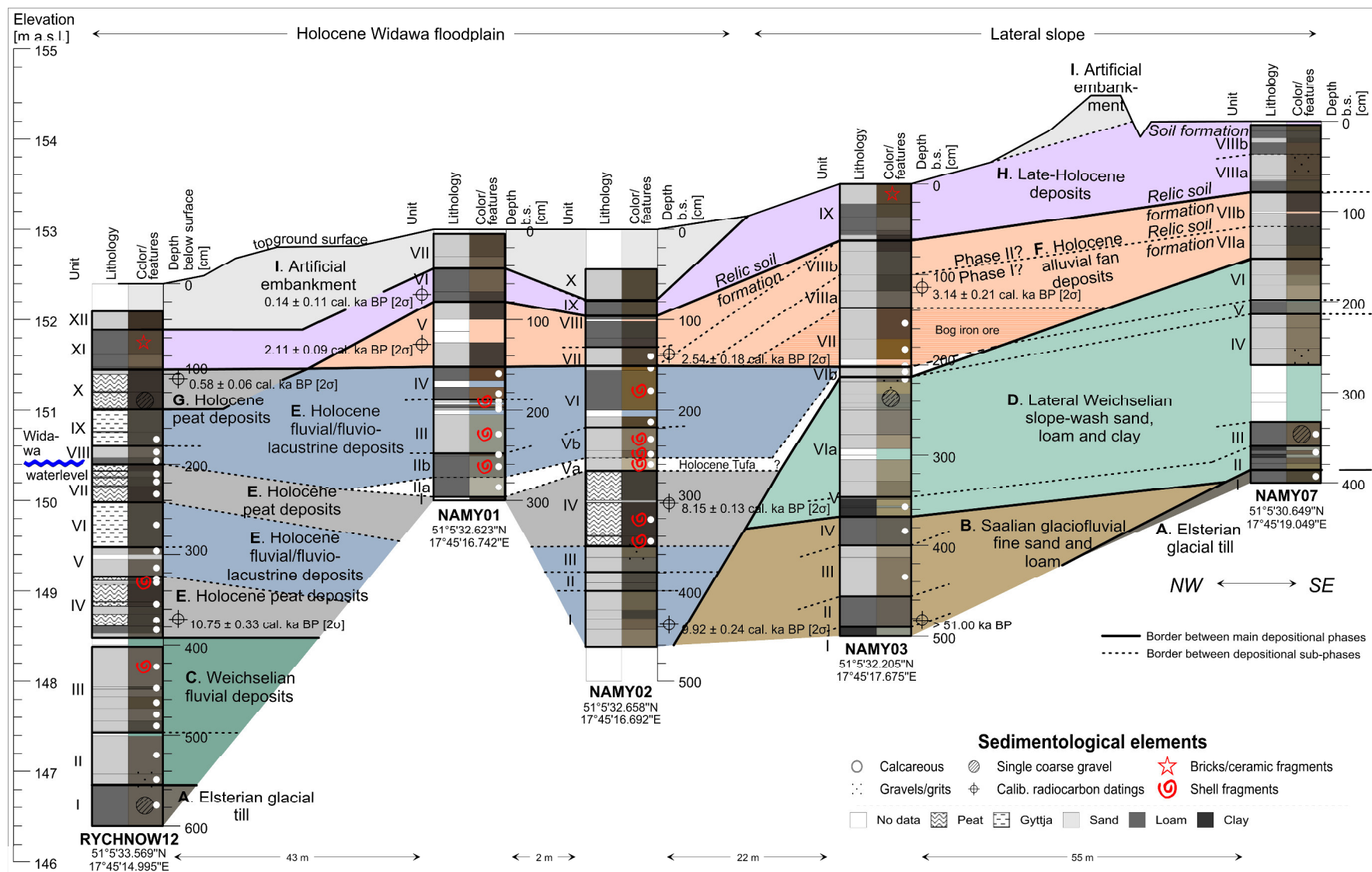


Fig. 5: Drilling transect at Rychnów I.

Nine main depositional phases are distinguished for transect Rychnów I:

A. Elsterian glacial till: The oldest sediments are detected at the bases of profiles RYCHNOW12 (unit I) and NAMY07 (unit I). Both units are characterized by carbonate-containing, badly sorted, coherent loam with single coarse gravels (Fig. 5), typical for regional glacial till deposits (Krzyszkowski and Kuszell, 2007). Correlation between both units is supported by similar MS-, pH- and EC-values (Fig. 6). Since these layers cannot be associated with Saalian glacial till deposits of the Warthe stadial, which occur at the surface of the local upslope area (Fig. 2), these deposits are assigned to glacial formations of the Elsterian glacial period, corresponding to the parent material in the northern part of the study area, outcropping below 150 to 160 m a.s.l. (Bartczak, 1997).

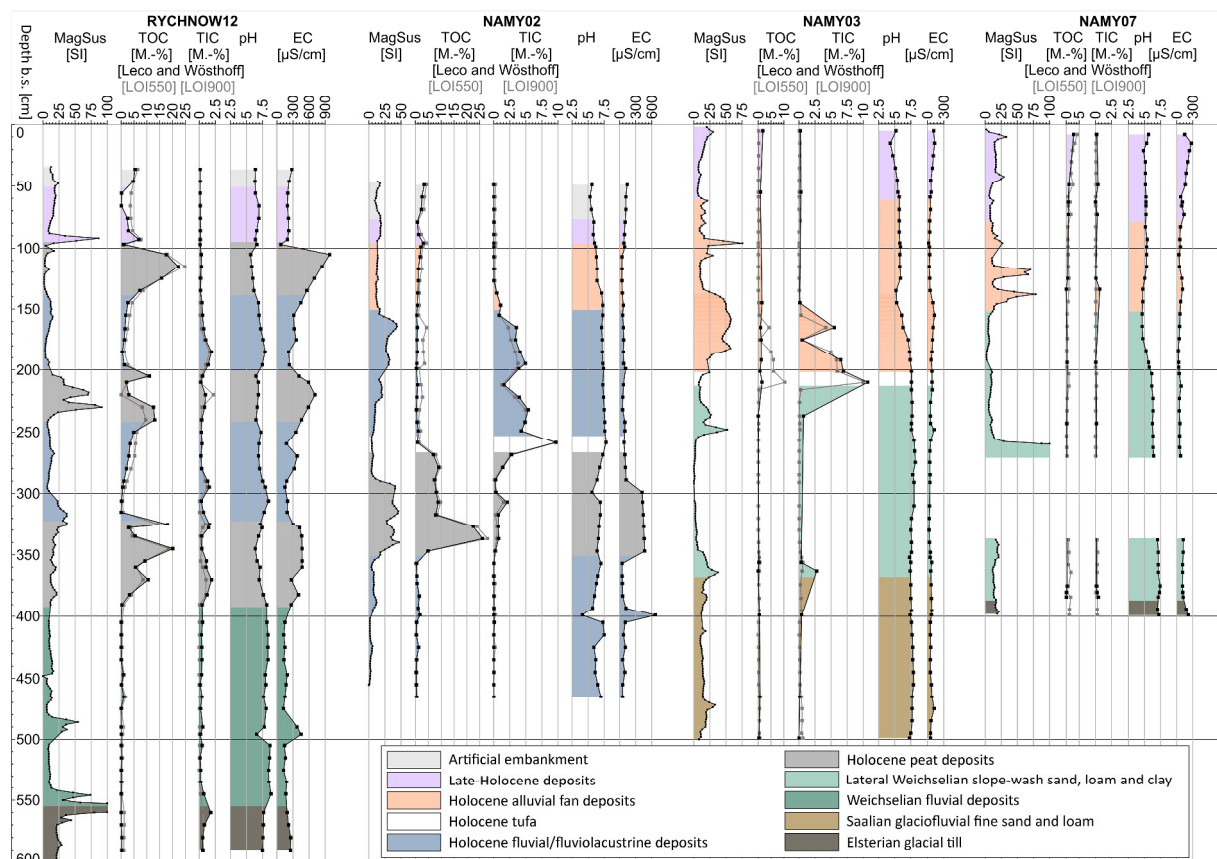


Fig. 6: Bulk sediment chemistry of the profiles RYCHNOW12, NAMY02, NAMY03 and NAMY07 comprising MS-, TOC-, TIC-, pH- and EC-values.

B. Saalian glaciofluvial fine sand and loam: A calcareous succession of clay, loam and sand at profile NAMY03 (unit I-IV) dates to an age of more than 51 ka BP (482 cm depth below surface (b.s.); Fig. 3) and is therefore older than the Weichselian middle pleniglacial (Fig. 3). These sediments are interpreted as Saalian glaciofluvial deposits due to their relative position, also confirmed by Cincio (1997), who mapped outcropping Saalian glaciofluvial deposits superimposing Elsterian glacial deposits in the direct vicinity of the transect (Fig. 4D). Since

these basal Elsterian and Saalian sequences are neither detected in the present floodplain (profiles RYCHNOW12 and NAMY02) nor at the upper profile NAMY07, they were either eroded before younger Pleistocene deposits accumulated or not deposited at these locations (Fig. 5).

C. Weichselian fluvial deposits: In the floodplain (profile RYCHNOW12, units II and III) well-sorted, fine-grained and -layered, fine gravel-bearing sands with shell fragments, syndimentary carbonate contents (between 1.4 and 5.8 mass% CaCO_3), SOM contents of up to 2.0 mass% and particularly high pH values of up to 8.8 occur, which are interpreted as Weichselian fluvial deposits. The MS-peaks in these formations (Fig. 6) probably result from the gravel interlayers (Fig. 5).

D. Lateral Weichselian slope-wash sand, loam and clay: At profile NAMY03 (unit V) and NAMY07 (unit II) slightly carbonatic (between 0.2 and 0.5 mass% CaCO_3), thinly layered clay was deposited, followed by fine gravel-bearing (fine) sand (profiles NAMY03, unit VIa and NAMY07, unit IV) with significantly low MS-values (Fig. 6). The stratigraphic position, the low carbonate contents and the fine succession of clays, loams and sands point to lateral Weichselian slope-wash sand, loam and clay deposits from the lateral valley. This corresponds to observations described by Cincio (1997) for the immediate vicinity of the transect (Fig. 4B). These formations, identified in profiles NAMY03 and NAMY07, deposited as Pleistocene alluvial fan deposits at the mouth of a local tributary into the Widawa valley (Figs. 4B and 5). The MS-peak at profile NAMY07 (unit IV) is ascribed to the coarse gravel contents. In contrast, profiles RYCHNOW12, NAMY01 and NAMY02 lack lateral Weichselian slope-wash formations. These deposits possibly reached further into the Widawa floodplain but might be eroded by the late-Pleistocene, braided Widawa.

E. Holocene fluvial/fluviolacustrine tufa and peat deposits: During the early Holocene, units of peats, gyttja and fine sand with significant organic contents were formed or deposited. Profile RYCHNOW12 (unit IV) shows fluviolacustrine peat deposits with shell fragments that date to 10.75 ± 0.33 cal. ka BP (371 cm depth b.s.; Fig. 3), which corresponds to the Preboreal of the Blytt-Sernander sequence at the beginning of the Holocene (Table 1; Fig. 3). The (loamy) sands at the same absolute depth of 149 m a.s.l. at profile NAMY02 (unit I) are dated slightly younger at 9.92 ± 0.24 cal. ka BP (Fig. 3), which corresponds to the Boreal (Table 1; Fig. 3). All peat layers are characterized by distinctly increased MS-, EC- and TOC-values equivalent to up to 52.2 mass% SOM (Fig. 6). Subsequently, at profile RYCHNOW12 (units V-VII), a succession of fine sand, gyttja and peat was formed in the Widawa floodplain,

pointing to a succession of fluvial and fluviolacustrine facies as described by Helbig and De Klerk (2002). Due to texture, TOC-contents and position of the peat layers at profiles RYCHNOW12 (unit VII), NAMY01 (unit I) and NAMY02 (unit IV), it is suggested that these layers represent a coherent formation (Fig. 5). At profile NAMY02 (unit IV) this formation dates to 8.15 ± 0.13 cal. ka BP (Fig. 3), and thus to the Atlantic period (Table 1; Fig. 3). At profiles NAMY01 (unit IIa), NAMY02 (unit Va) and NAMY03 (unit VIb) these layers are followed by particularly carbonate tufa layers with carbonate contents between 80.8 and 89.1 mass% CaCO_3 (Fig. 6). As these formations are directly situated on top of Atlantic peat layers (profiles NAMY01 and NAMY02; Fig. 5) they probably also precipitated during this warmer and very humid period, as is typical for tufa layers throughout northern Central Europe (Goudie et al., 1993; Dabkowski, 2014; Ford and Pedley, 1996). Carbonates often precipitate at or close to the surface when dissolved CO_2 degasses from carbonate-containing groundwater due to increasing temperatures and decreasing pressure (Griffiths and Pedley, 1995). The similarly high carbonate contents at profiles NAMY02 and NAMY03 indicate that these tufa layers can be traced in these profiles and that their difference in altitude represents the relief of the former surface (Fig. 5). The overlying deposits at profiles RYCHNOW12 (units VIII and IX), NAMY01 (units IIb, III and IV) and NAMY02 (units Vb and VI) again include shell fragments, typical for the local floodplain deposits, and therefore point to Holocene floodplain deposits (Fig. 5). Especially at profile NAMY02 these layers show distinctly increased MS-values and TIC-contents (Fig. 6).

F. Holocene alluvial fan deposits: During the late Holocene the local alluvial fan was reactivated at the mouth to the Widawa floodplain and deposited sandy material, as found in profiles NAMY03 (units VII and VIII) and NAMY07 (unit VII). At profile NAMY03 these layers date to the Late Bronze Age (3.14 ± 0.21 cal. ka BP; 114 cm depth b.s.; Fig. 3). In unit VII these deposits are strongly cemented and dominated by hydromorphic features and iron concretions, which – according to Puttkammer (2012) – point to bog iron ore layers. The iron in this formation is a secondary deposition, precipitated post-sedimentarily by flows of iron-containing groundwater in the zone of groundwater oscillation (Puttkammer, 2012). This layer is also characterized by decreased pH values and increased MS-values as well as TIC-contents equivalent to up to 45.9 mass% CaCO_3 (Fig. 6). The following distinct MS-peaks at profiles NAMY03 (between units VIIa and VIIb) and NAMY07 (between units VIIa and VIIb) indicate that the deposits of both sediment sequences belong to the same depositional succession, which is divided into two phases (Figs. 5 and 6). Each of the lower units, unit VIIa (NAMY03) and VIIa (NAMY07), is characterized by at least a short post-sedimentary

pedogenesis, identified due to the increasingly dark soil color and a SOM increase of up to 1.9 mass% SOM (NAMY07, unit VIIa; Fig. 5) with decreasing depth (Morgan, 2005). Subsequently, in unit V of profile NAMY01 and units VII and VIII of profile NAMY02, sandy loam and loamy sand deposited. At profile NAMY02 these sediments date to the early pre-Roman period (2.54 ± 0.18 cal. ka BP; 138 cm depth b.s.; Fig. 3; Table 1) and at profile NAMY01 to the late pre-Roman period (2.11 ± 0.09 cal. ka BP; 127 cm depth b.s.; Fig. 3). Several arguments indicate that these layers were also deposited as part of the tributary's alluvial fan formation: (i) The contour line at 152 m a.s.l. in Fig. 4B shows that profiles NAMY01 and NAMY02 are situated within the depositional zone of the alluvial fan. (ii) The grain size composition of these formations is finer than the alluvial fan deposits at profiles NAMY03 and NAMY07 (Fig. 5), which corresponds to the downslope fining that characterizes alluvial fans (Superson et al., 2015). (iii) The ^{14}C -dates, which are dedicated to the alluvial fan deposits (Fig. 5), show younger ages to the northwest, which reflects the direction of expansion of the alluvial fan. Also the organic contents of up to 7.4 mass% SOM (profile NAMY02, unit VIII) are not particularly high for originary alluvial deposits (Zygmunt, 2009), but can also be explained by post-sedimentary SOM enrichment during the subsequent pedogenesis (Morgan, 2005).

G. Holocene peat deposits: At profile RYCHNOW12 (unit X), a third peat layer was formed, indicating another fluviolacustrine phase in the Widawa floodplain, dated to the Late Medieval period (0.58 ± 0.06 cal. ka BP; Fig. 3).

H. Late-Holocene deposits: Following this peat layer, profiles RYCHNOW12 (unit XI), NAMY01 (unit VI), NAMY02 (unit IX), NAMY03 (unit IX) and NAMY07 (unit VIII) were covered by layers of (sandy) loams and loamy sands with low organic carbon contents. It could not be determined whether these deposits are coherent alluvial or colluvial formations. While humus contents of up to 12.0 mass% SOM (profile RYCHNOW12, unit XI) point to colluvial formations (Smolska, 2007), their location in the river valley and outside of the footslope typically rather points to an alluvial deposition (Fuchs et al., 2010). At profile NAMY01 at a depth of 72 cm b.s. these layers date to modern periods (0.14 ± 0.11 cal. ka BP; Fig. 3). At profiles NAMY03 (unit IX) and NAMY07 (unit VIII) these layers represent the recent topsoil.

I. Artificial embankment: At profiles RYCHNOW12 (unit XII), NAMY01 (unit VII) and NAMY02 (unit X) the topsoil is characterized by (silty) sand and interpreted as an artificial

embankment to stabilize the pathway along which the lower part of the transect was conducted in the Widawa floodplain (Fig. 5).

Transect Rychnów II shows a succession of Saalian glaciofluvial to late-Holocene deposits comprised sandy, silty and loamy sediments with varying carbonate and organic carbon contents, as well as Holocene colluvial layers (Fig. 7). Downslope of transect Rychnów II the 4 m deep profile RYCHNOW13 is characterized by decreasing grain size with decreasing depth, reaching from sand to loam, overlain by a sandy topsoil. Units III and IV are distinctly darker containing ceramic/brick fragments. In contrast, the 4 m deep upper profile RYCHNOW17 shows a relatively fine stratigraphy dominated by loamy deposits with a sandy topsoil (Fig. 7).

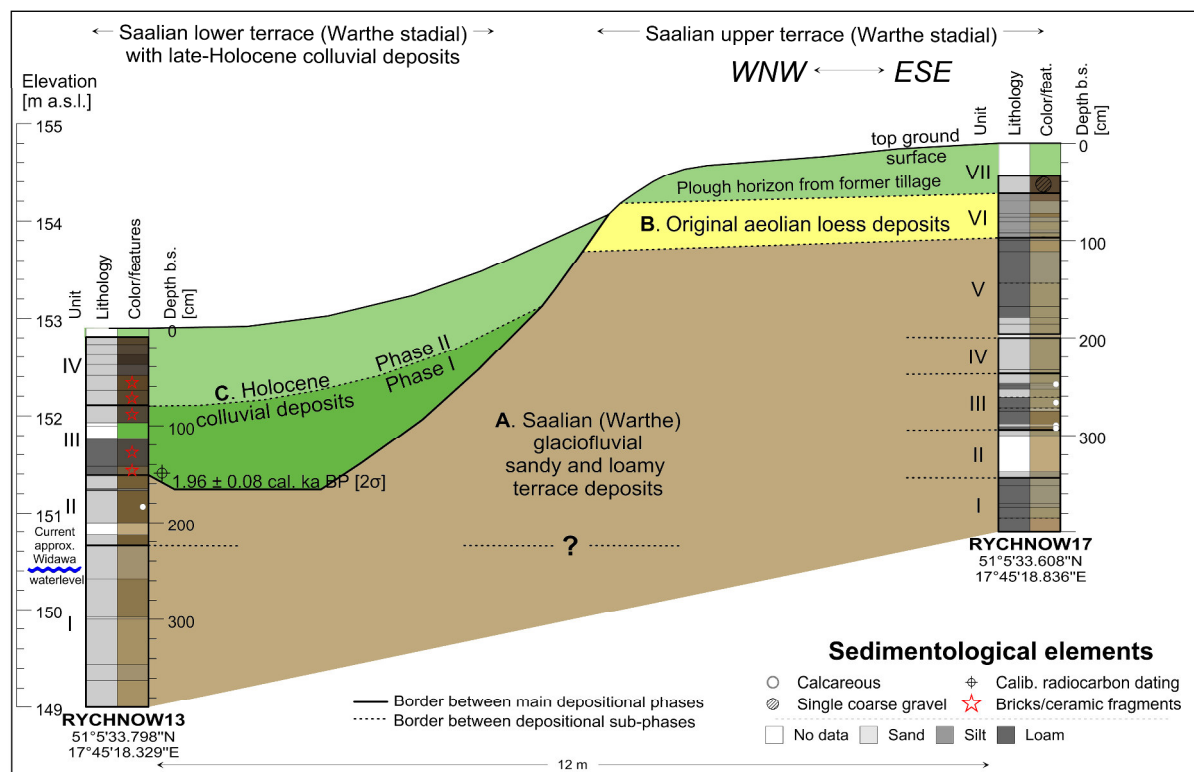


Fig. 7: Drilling transect at Rychnów II.

Three main depositional phases are distinguished for the transect Rychnów II:

A. Saalian (Warthe) glaciofluvial sandy and loamy terrace deposits: According to the geology (Cincio, 1997) and topography (Fig. 4B) the transect is situated at the transition between an older upper (profile RYCHNOW 17) and a younger lower (profile RYCHNOW13) glaciofluvial terrace level of the Warthe stadial. Due to the lack of ^{14}C -datable material a further absolute chronology was not possible. Nevertheless, the

moderately sorted, mostly sandy and loamy grain size and the calcareous layers on different levels of the middle section at profiles RYCHNOW13 (unit II) and RYCHNOW17 (unit III) are characteristic for glaciofluvial deposits (Raukas and Stankowski, 2005), although gravels are not detected in these formations. The lower glaciofluvial terrace level of 151.5 m a.s.l. at profile RYCHNOW13 suggests – as a hypothesis – that a glaciofluvial or fluvial erosion event removed postulated overlain deposits at RYCHNOW13, which today only remained as upper terraces at RYCHNOW17.

B. Original aeolian loess deposits: The upper part of profile RYCHNOW17 (unit VI) is characterized by a layer of very well-sorted, unstratified, silty deposits without particles > 2 mm, which, according to Krajcarz et al. (2015), indicates an original loess layer. Although loess is typical for periglacial Pleistocene landscapes (Krajcarz et al., 2015), the study area is not known for vast loess accumulations (Ralska-Jasiewiczowa, 1983; Bartczak, 1997; Cincio, 1997) and the detected formation accordingly only represents a relatively thin loess layer, which was not further temporally classified.

C. Holocene colluvial deposits: The upper part of profile RYCHNOW13 (units III and IV) shows (at least) two phases of Holocene colluvial depositions. The base of the first accumulation phase at profile RYCHNOW13 (unit III) dates to the beginning of the Roman period (1.96 ± 0.08 cal. ka BP; Fig. 3). This phase is characterized by a 54 cm thick layer of sandy loam with increasing organic contents towards the top, indicating a more stable phase documented by a relic soil (Morgan, 2005). However, it is possible that increased Holocene sedimentation rates impeded the microbial decomposition of organic carbon in the soil sediments (Schütt, 2004). The second phase is characterized by a 71 cm thick sandy layer, which shows an advanced pedogenesis that clearly indicates another phase of stability (Fig. 7; Morgan, 2005). The location and age in combination with ceramic fragments of the lower colluvial phase enable a classification as a cultural layer possibly related to the prehistoric slag sites of Rychnów 7 and 8 (AZP, since 1978), which are situated directly upslope of this transect (Fig. 4B). In contrast, the upper colluvial phase is of younger age, showing the current pedogenesis. The location of profile RYCHNOW17, downslope of an agricultural field currently in use and directly upslope of a terrain step, points to a dynamic situation regarding the erosion and accumulation of sediments. The clear transition involving a change in the grain size between top- and subsoil at a depth of 25 cm indicates a plough horizon caused by former tillage (Fig. 7).

4.2.2 Study site of Lubska

The study site of Lubska is situated downstream of Rychnów and west of the town Namysłów (Fig. 4A), located in the direct vicinity of a prehistoric iron slag site. The site is geomorphologically characterized by Weichselian terraces along the Holocene Widawa floodplain. In the vicinity of this site Elsterian glacial till crops out (Fig. 2). The drilling transect at Lubska includes three drillings (profiles LUBSKA09, LUBSKA10 and LUBSKA11), which are situated in the transition zone between the Holocene Widawa floodplain composed of fluvial sandy silt (Bartczak, 1997) and Weichselian terraces made of fluvial sand, loam and gravels (Fig. 4C).

The transect shows a succession of Elsterian glacial till, aeolian sands and Holocene deposits made of sandy, silty and loamy sediments with varying carbonate and organic carbon contents (Fig. 8). At this transect the downslope profile LUBSKA09 is characterized by a relatively fine-layered stratigraphy, which mostly consists of fine gravel-bearing sand alternating with fine organic-rich layers below the depth of 2 m b.s. (units II-V; Fig. 8). From base to top the 3 m deep footslope profile LUBSKA10 shows loamy deposits with decreasing carbonate contents (units I and II), followed by carbonate-free sand (unit III). The topographically uppermost profile LUBSKA11 is 3 m deep and shows a loamy base (units I and II), followed by sand (from unit III) with ceramic/brick fragments in the topsoil (units IVb and c; Fig. 8).

Five main depositional phases are distinguished for the transect at Lubska:

A. Elsterian glacial till: The base (units I) of each of the profiles shows slightly to moderately carbonate-containing, badly-sorted (sandy) loam with a coherent texture and content of fine gravel (profile LUBSKA09) or single coarse gravels (profiles LUBSKA10 and LUBSKA11; Fig. 8). The grain size distribution is badly sorted, varying between coarse clay and sand (particle size curves in the Appendix, Figs. A2.1.5, A2.2.3 and A2.3.4). In total these characteristics refer to glacial till deposits (Krzyszowski and Kuszell, 2007). In accordance with the geological map (Fig. 2), these formations are assigned to glacial formations of the Elsterian glacial period, covered by Weichselian and Holocene deposits at the left Widawa river bank (Fig. 2).

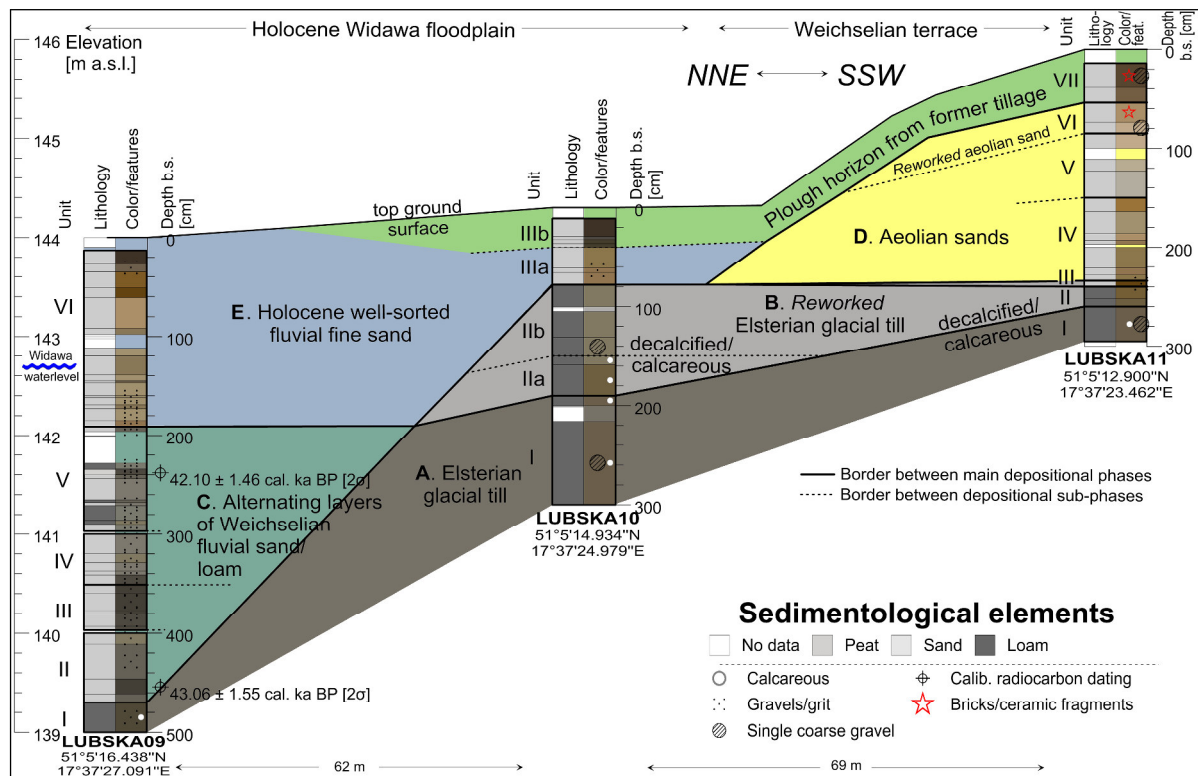


Fig. 8: Drilling transect at Lubska.

B. Reworked Elsterian glacial till: Units II at the profile LUBSKA10 and LUBSKA11 display slightly better-sorted and partly decalcified sediments of similar texture compared to the underlying glacial till (unit I; Appendix, Fig. A2.2.2). Correspondingly, these units are interpreted as *reworked* Elsterian glacial till. It cannot be determined whether this reworking took place subglacially by meltwaters or post-sedimentarily involving weathering and decalcification processes (Wozniak and Czubla, 2015).

C. Alternating layers of Weichselian fluvial sand/loam: The absence of the (reworked) Elsterian glacial till deposits in the Widawa floodplain at profile LUBSKA09 to a level of c. 139.3 m a.s.l. is interpreted as a result of subsequent erosion that removed these deposits down to this level. Subsequently, at LUBSKA09 (units II-V) well-sorted fluvial medium sands and gravels deposited, superimposing the till deposits. The fine and heterogeneous structure of these c. 2.7 m thick formations points to several accumulation phases. Radiocarbon at depths of 454 cm b.s. (43.06 ± 1.55 cal. ka BP) and 238 cm b.s. (42.10 ± 1.46 cal. ka BP) match to the relatively short period of the Hengelo interstadial of the Weichselian middle pleniglacial period (MIS 3; Table 1).

D. Original and reworked aeolian sands: At LUBSKA11 (units IV-V) layers of very well-sorted (Appendix, Figs. A2.3.2 and A2.2.3), well-rounded, stratified and cross-bedded fine

sands without particles > 2 mm are detected. These characteristics rather point to aeolian than to fluvial depositions (Maaß et al., 2010). These formations are not dated and recorded in the geological map (Bartczak, 1997) and were therefore not temporally classified. However, Weichselian aeolian sands typically occur in small-scale accumulations along the floodplain of the Widawa River (Fig. 2). Nevertheless, due to overlying soil development a younger period of dune formation during the medieval is not assumed. On top of these formations at LUBSKA11 (unit VI) similarly well-sorted sands with a bimodal particle size distribution (Appendix, Fig. A2.3.1) and scattered medium gravels accumulated (LUBSKA11, unit VI), which are interpreted as reworked aeolian sands.

E. Holocene well-sorted, fluvial fine sand: During a subsequent incision phase parts of the Weichselian deposits were probably eroded, before well-sorted Holocene fine and medium sands accumulated at profiles LUBSKA09 and LUBSKA10. The location and the partly embedded gravels indicate a fluvial genesis. Subsequently, before the vicinity of the study site was used as pastureland, the margins of the Widawa floodplain were used for arable farming, as the clear 30 cm deep boundaries of the organic-rich topsoil at profiles LUBSKA10 (unit IIIb) and LUBSKA11 (unit VII) indicate (Fig. 8; Bausenwein et al. 2008).

4.2.3 Study site of Młokicie

The study site of Młokicie is situated between the sites of Lubska and Pielgrzymowice (Fig. 4A) and represents a site at the margins of the Widawa floodplain, where the Holocene Widawa incised into Saalian glacial till (Fig. 2). In contrast to the other study sites, this site has no spatial association with known archaeological sites (Fig. 4D). The drilling transect at Młokicie includes three drillings (profiles NAMY06, NAMY04 and NAMY05) and covers the margin of the Widawa floodplain. The topography of the site is characterized by a clear terrain step along the floodplain, which is reflected in the different height levels between profiles NAMY04 and NAMY05. The transition zone from the Holocene Widawa floodplain to the lateral Saalian glacial till of the Drenthe stadial is situated in the southwest of the transect (Fig. 4D).

The transect shows a succession of fluvial Weichselian and Holocene deposits that comprises sandy, silty and loamy sediments with varying carbonate and organic carbon contents (Fig. 9). The 4 m deep lower profile NAMY06 is characterized by an alternating sequence of gravelly loam (units I, III, V and VII) and sand (units II, IV, VI and VIII) with a distinct topsoil most recently transformed by tillage (Fig. 9). The 2 m deep profile NAMY04, located at the foot of the terrace can also be described by a multiple sequence of mostly gravelly loam (units I, III

and V) and sand (units II and IV). The 2 m deep NAMY05, located on the upper Holocene terrace level, is characterized by alternating sequences of loam (units I and III) and sand (units II and IV; Fig. 9).

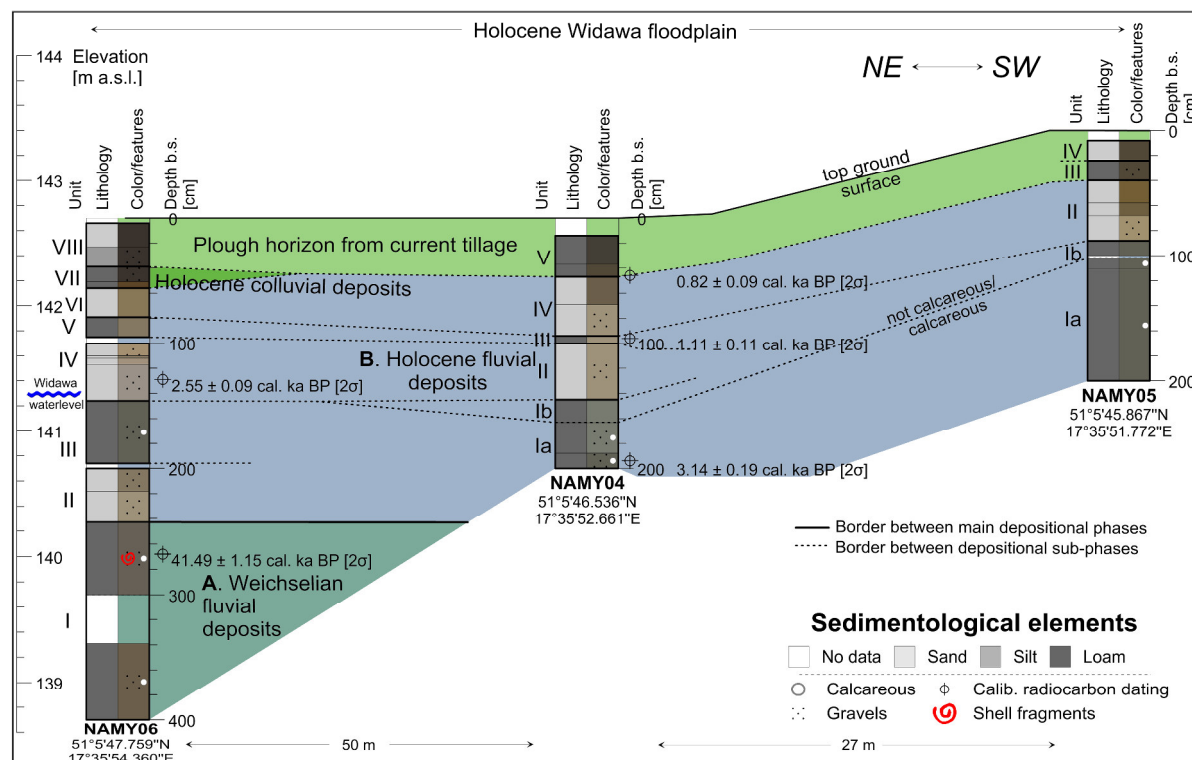


Fig. 9: Drilling transect at Młokicie.

Two main depositional phases are distinguished for the transect at Młokicie:

A. Weichselian fluvial deposits: At the bases of profile NAMY06 (unit I) the carbonate-containing, badly-sorted sandy loam with fine gravels and shell fragments dates to 41.49 ± 1.15 cal. ka BP (268 cm depth b.s.; Fig. 3) and therefore corresponds to the Weichselian deposits of the Hengelo interstadial detected at Lubska (MIS 3; Table 1).

B. Holocene fluvial deposits: Subsequently, Holocene gravelly fluvial sand and slightly carbonatic fluvial sandy loams were deposited at profile NAMY06 (units II and III), of which the latter is parallelized to the calcareous (gravelly) sandy loam of the Holocene base of profiles NAMY04 (unit Ia) and NAMY05 (unit Ia). For profile NAMY04 these deposits are dated to the Late Bronze Age (3.14 ± 0.19 cal. ka BP; 194 cm depth b.s.; Fig. 3). At profiles NAMY04 and NAMY05 the upper part of these layers are decalcified. At profiles NAMY06 (unit IV) and NAMY04 (unit II) gravelly fluvial sands subsequently deposited, which for profile NAMY06 are dated to the pre-Roman Iron Age (2.55 ± 0.09 cal. ka BP; 129 cm depth b.s.; Fig. 3). These deposits are overlain by fluvial (sandy) loam at profiles NAMY06 (unit V)

and profile NAMY04 (unit III). For NAMY04 (unit III) these loams are dated to the Early Medieval period (1.11 ± 0.11 cal. ka BP; 96 cm depth b.s.; Fig. 3). Successively, fine gravel-bearing fluvial sand was uniformly deposited at all profiles, NAMY06 (unit VI), NAMY04 (unit IV) and NAMY05 (unit II). At profile NAMY06 (unit VII) the base of the 52 cm thick organic topsoil has the character of a colluvial deposition. For profile NAMY04 the accordant layer (unit V) dates to the High Medieval period (0.82 ± 0.09 cal. ka BP; 46 cm depth b.s.; Fig. 3). The 30 cm deep organic-rich layers with a clear boundary in the profiles are characteristic for the current plough horizon (Bausenwein et al., 2008).

4.2.4 Study site of Pielgrzymowice

The study site of Pielgrzymowice represents the most western site (Fig. 4A) and is situated in the direct vicinity of a previously investigated prehistoric iron smelting site (Fig. 4E; Thelemann et al., 2016). The transect includes three drillings (profiles PIELW14, PIELW15 and PIELW16) and covers the transition from the Holocene Widawa floodplain, over the Weichselian terrace to lateral Weichselian slope-wash deposits in the northern part of the widening tributary valley (Fig. 4E).

The transect shows a succession of Saalian, Weichselian and Holocene deposits consisting of sandy, silty and loamy sediments with varying carbonate and organic carbon contents (Fig. 9). The 4 m deep downslope profile PIELW14 is characterized by sand predominating in the lower (units I-III) and middle part (unit IV) and loam characterizing the overlying layers (unit V; Fig. 10). The 3 m deep slope profile PIELW15 shows sandy (units I and V) and badly-sorted silty deposits (units II and IV) with an embedded c. 20 cm thick loamy layer (unit III). The 3 m deep upslope profile PIELW16 is characterized by loam with a number of scattered gravels (units I-III) and a sandy topsoil (unit IV; Fig. 10).

Seven main depositional phases can be distinguished for the transect at Pielgrzymowice:

A. Saalian glacial till: The oldest sediments are detected at the base (unit I) of the upslope profile PIELW16 and are assigned to the Saalian glacial till that represents the subsurface in the vicinity of Pielgrzymowice (Fig. 4E). These sediments are characterized by carbonate-containing, badly sorted, coherent, unstratified, sandy loam embedded with single coarse gravels (Fig. 10), which is again typical for regional glacial tills (Krzyszowski and Kuszell, 2007).

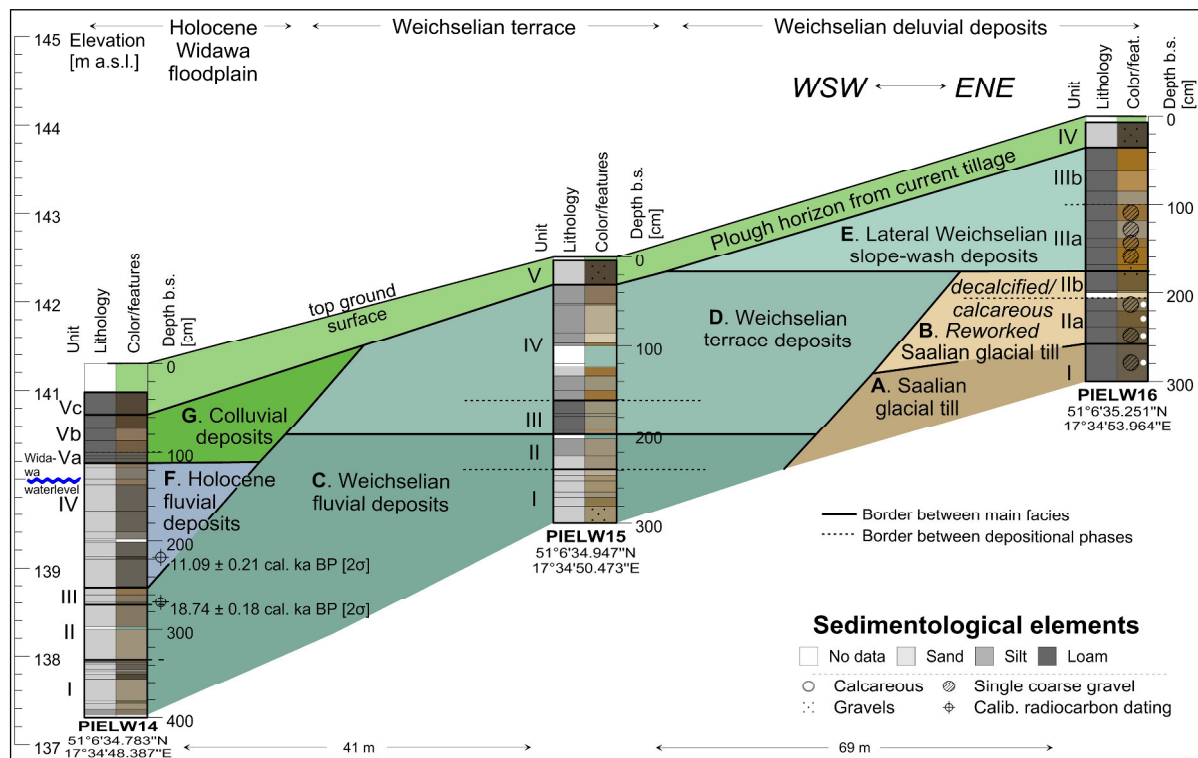


Fig. 10: Drilling transect at Pielgrzymowice.

B. Reworked Saalian till: On top of the Saalian glacial till in profile PIELW16, partly decalcified, slightly layered and well-sorted sandy loam with single coarse gravels (unit II) occurs. Due to their similar texture these formations are interpreted as reworked Saalian glacial till deposits. The decalcification can either be attributed to a sub- or post-glacial reworking (Wozniak and Czubla, 2015) combined with chemical weathering or relic soil-forming processes, e.g. during the Eemian interglacial (Table 1; Jary, 2009).

C. Weichselian fluvial deposits: After a subsequent incision phase that eroded the autochthonous and reworked Saalian till at profiles PIELW14 and PIELW15 along the Widawa floodplain, well-sorted, fine-grained and -layered fluvial sands with significant organic contents deposited at profiles PIELW14 (units I-III) and PIELW15 (units I and II). At profile PIELW14 these fluvial deposits dated to the late-Weichselian glacial period (18.74 ± 0.18 cal. ka BP; 269 cm depth b.s.; Fig. 3).

D. Weichselian terrace deposits: The following loamy texture at profile PIELW15 (unit III) indicates a facies change. In accordance with the geological map (Bartczak, 1997) these formations are interpreted as Weichselian terrace deposits.

E. Lateral Weichselian slope-wash deposits: Subsequent to the Weichselian terrace deposits, laterally deposited sandy loams with single coarse gravels accumulated at profile PIELW16 (unit III), originating from the local tributary. Corresponding to Bartczak (1997), these

sediments are interpreted as lateral Weichselian slope-wash deposits (Fig. 4E). A comparison of the level of the Weichselian deposits in profiles PIEL14 and PIEL15 points to another incision phase along the Widawa floodplain to a level of c. 139 m a.s.l.

F. Holocene fluvial deposits: In profile PIELW14 (unit IV) overlying fine layered sands with alternating humus contents occur and date to 11.09 ± 0.21 cal. ka BP (218 cm depth b.s.; Fig. 3). They can thus be assigned to the Preboreal at the beginning of the Holocene (Fig. 3, Table 1).

G. Colluvial deposits: At profile PIELW14 (unit V) organic rich (sandy) loams accumulated as colluvial deposits at the transition between slope and floodplain, possibly induced by the prehistoric settlement and smelting activities (Thelemann et al., 2016). The uppermost 30 cm deep organic-rich layers with a clear lower boundary represent the current plough horizon of the present tillage (Fig. 10; Bausenwein et al., 2008).

4.3 Late-Quaternary landscape evolution

During the Elsterian glacial period (MIS 12; Table 1) the oldest preserved near-surface deposits of the study area accumulated (Bartczak, 1997). These glacial till deposits crop out in different areas mainly along the Widawa floodplain (Fig. 2) and represent typical parent material, forming the subsurface of the Saalian plateaus in the study area (Bartczak, 1997). These deposits are documented at the bases of transects Rychnów I (Fig. 5; profiles RYCHNOW12 and NAMY07) and Lubska (Fig. 8; profiles LUBSKA10 and LUBSKA11).

After the subsequent Holsteinian interglacial (MIS 11; Table 1), during the Drenthe stadial of the Saalian complex, glaciofluvial fine sands and loams deposited on the Elsterian base and today crop out at the eastern and western slopes of the Widawa valley in the vicinity of Rychnów (Fig. 2), as shown at the base of transect Rychnów I (Fig. 5; profile NAMY03).

With the Drenthe ice advance (MIS 6; Table 1) glacial till was subsequently deposited, which is today preserved on plateaus of the study area (Fig. 2) and localized as basal unit of transect Pielgrzymowice (Fig. 10; profile PIELW16). The northwest to southeast orientation of the eskers in the northwest of Namysłów (Fig. 2) indicates that this ice advance crossed the area from northwest to southeast (Fig. 11A). Accordingly, for this stage Liedtke (1981) mapped a glaciogenic channel in the southeast of the study area (Fig. 1B), which formed the previous southeasterly discharge direction of subglacial melt waters parallel to the direction of the ice advance. It is suggested that the current discharge direction in southwestern direction, through the relatively narrow Widawa valley northeast of Namysłów, was blocked during this period

by sediments of the Drenthe ice advance (Fig. 1B). With the ice retreat during the late Drenthe stadial, the discharge direction changed to southeast. With the beginning incision of Drenthe meltwaters into the Saalian glacial till the late Pleistocene Widawa valley began to develop (Fig. 11B). The course of this valley was determined by the ice marginal position: near the ice margin the discharge direction ran southward, orthogonal to the ice marginal position, and then turned westward at Namysłów, parallel to the ice margin (Fig. 1B). Subsequently, still during the late Drenthe stadial, glaciofluvial sands and gravels deposited along the initial Widawa valley floor, as typical for braided river systems (Fig. 11C; Kaiser et al., 2012). Today these deposits are predominantly eroded and only preserved as upper Drenthe terraces along the Widawa floodplain (Fig. 2).

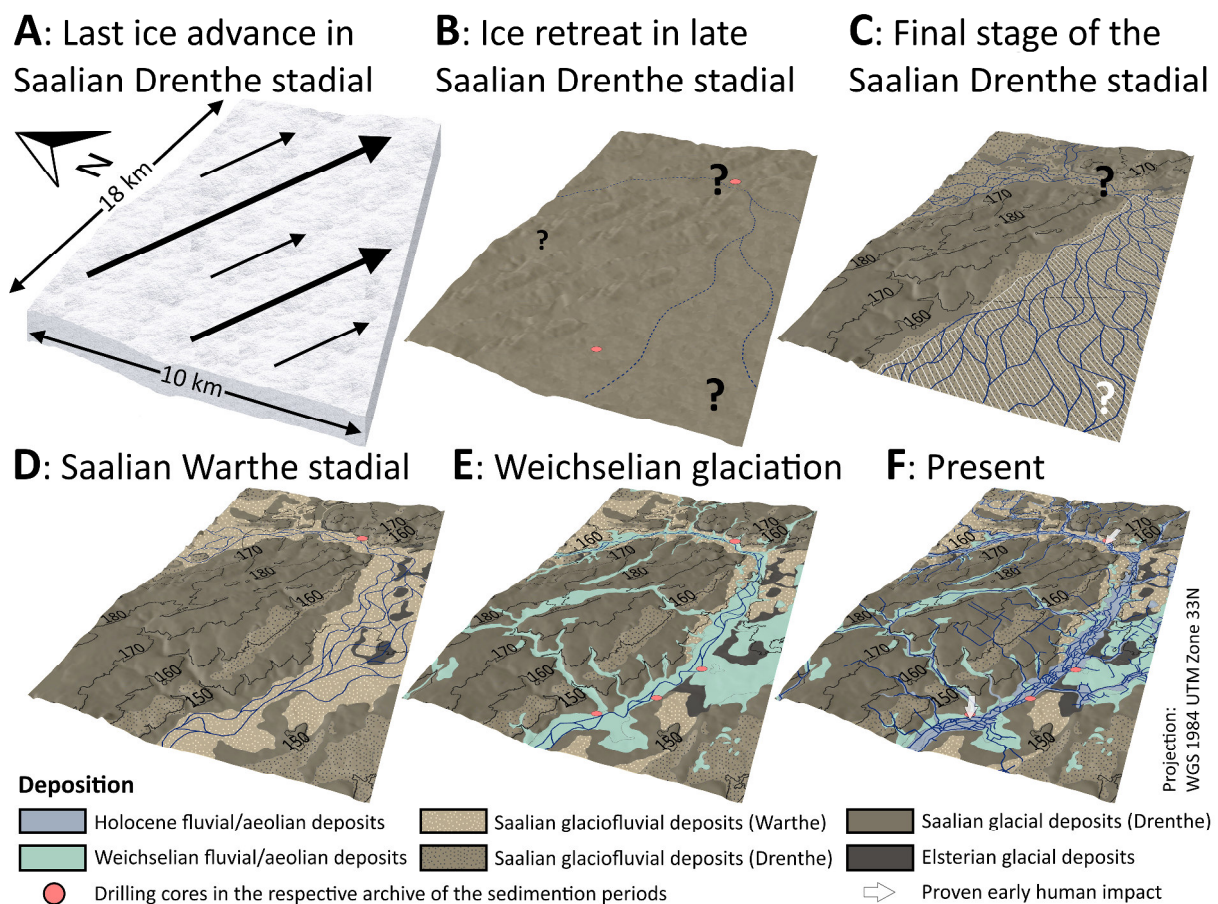


Fig. 11: Drafts of the landscape development from the last direct ice coverage to the present.

Data: 11A: Direction of ice advance derived from esker orientation, height of the ice sheet not true to scale; B to F: Surface models, deposits and river systems reconstructed and illustrated through a combination of the Geological detailed map 1 : 50.000 from Bartzak (1997), map sheet 0766, and Cincio (1997), map sheet 0767 and the present CODGiK (2013) LiDAR DEM (Generalized DEM with 10 m horizontal resolution, hillshade z-factor 3) with a focus on the terrace levels and the sedimentological records (Section 4). Present rivers from TK25 (1886-1938). Relief 20 times superelevated. Projection: WGS 1984 UTM Zone 33N.

Since the Seyda interstadial (Table 1), which followed the Drenthe stadial, but still belonged to MIS 6 (Table 1), the study area was situated in the periglacial zone and remained free of active glaciations (Liedtke, 1981). During the following Warthe stadial of the Saalian

complex the ice marginal position (Fig. 1B) was located c. 20 km north of the study area (Fig. 1B). During this period the Pleistocene melting waters enabled the Widawa to incise more than 15 m into the glacial tills. Subsequently, glaciofluvial sand and gravel accumulated along the floodplain (Figs. 2 and 11D), as documented in transect Rychnów II (Fig. 7; profiles RYCHNOW13 and RYCHNOW17). At this transect the sediments are characterized by rather loamy deposits without gravels but with very slight organic contents (Fig. 7; Appendix, Fig. A1.3). These characteristics rather point to an anastomosing river system (Gradzinski et al., 2000), as periglacial fluvial systems do not necessarily establish braided river systems (Vandenberghe, 2002). In transect Rychnów II a 37 cm thick layer of loess was deposited (unit VI). As the study area was located in the periglacial zone during the Warthe stadial (Fig. 1), these deposits are tentatively associated to this period (Fig. 7).

Before Weichselian fluvial deposits accumulated, the Widawa River further incised, either during the Eemian interglacial (MIS 5e; Table 1) or during the early Weichselian glacial period (MIS 5d to 2; Table 1), as the lower Weichselian terrace level indicates (transects Rychnów I and II, Figs. 5 and 7). According to the palynological investigations conducted in the northern part of the Widawa catchment area by Kuszell et al. (2007), the study area was predominantly free of woods during the early Weichselian glaciation, followed by plant successions during the Brörup interstadial (MIS 5c; Table 1). The palynological record allowed the reconstruction of different vegetation periods that represent a succession of climatic shifts from moderately cool, to milder conditions, and back to a cool climate (Kuszell et al., 2007). Similar climatic shifts might also be represented in the Weichselian fluvial deposits identified at the study sites of Rychnów I (Fig. 5; profile RYCHNOW12), Lubska (Fig. 8; profile LUBSKA09), Młokicie (Fig. 9; profile NAMY06) and Pielgrzymowice (Fig. 10; profile PIELW14), characterized by thin sequences of coarser and finer, more organic-rich sediments. At Lubska and Młokicie these deposits date to the Hengelo interstadial (MIS 3, Table 1) and at Pielgrzymowice to the late-Weichselian glacial period (Fig. 3). Particularly the well-sorted, thin-layered fine sands with organic contents of up to 2.0 mass% SOM at Rychnów I (profile RYCHNOW12) are furthermore characteristic for an anastomosing river system (Watters and Stanley, 2007), while the badly-sorted, coarse fluvial sediments at Lubska and Młokicie rather point to braided river deposits (Gruszka et al., 2012). This distinction of the Weichselian discharge system is also supported by the character of the valley cross section. While the upper Widawa reaches are characterized by a relatively narrow valley, which – in combination with vegetation – facilitates the development of a few rather stable drainage channels (Hickin, 1984), the lower reaches are characterized by a flatter and

wider valley bottom fed by additional tributaries (Fig. 1B), allowing seasonally strong alternating discharges in a wide braided riverbed divided into branches and barriers (Williams et al., 2015). Further subsequent Weichselian accumulations are identified as flood terrace deposits at Pielgrzymowice (profile PIELW15). Particularly during the later Weichselian glacial period corresponding to a Widawa valley incision of approximately 2 m, the lateral Widawa valleys also incised and lateral Weichselian slope-wash sand, loam and clay deposited (Bartczak, 1997; Cincio, 1997), as documented at Rychnów I (Fig. 5; profiles NAMY03 and NAMY07) and Pielgrzymowice (Fig. 10; profile PIELW16). During this period fluvial loams and aeolian sands and dunes also accumulated in the study area. Due to the lack of dating material a geochronological classification of such deposits extracted at Lubska could only be bracketed by the stratigraphy and suggests an assignment to the Weichselian period or younger (Figs. 2 and 8).

Prior to the Holocene, another incision phase can be derived by comparing the elevation levels of the Weichselian terrace deposits with the Holocene deposits at Pielgrzymowice (Fig. 10). The Holocene deposits in the upper reaches of the study area, characterized by peats and peaty silts, point to a continuation of an anastomosing river system (Watters and Stanley, 2007; Gradzinski et al., 2000). Whether this peat formation was induced by an elevated erosion base coming from a mid- to late-Holocene sea-level rise in the Baltic Sea basin, as it is described by Kaiser et al. (2012) for Germany and Poland, could not be verified. In contrast, the lower reaches, characterized by fluvial sands and gravels as well as sandy silts (Fig. 2), localized at Lubska (Fig. 8; profile LUBSKA09), Młokicie (Fig. 9; profiles NAMY06, NAMY04 and NAMY05) and Pielgrzymowice (Fig. 10; profile PIELW14), rather indicate a meandering or braided river system (Vandenberghe, 2002). Particular to the Holocene is the calcareous Atlantic tufa layer at transect Rychnów I. During the late Holocene the anastomosing river system expanded to the lower reaches of the Widawa and further incised (TK25, 1886-1938).

Earliest evidence of human impact on the landscape is reflected in the alluvial fan deposits at Rychnów and dated on the basis of a charcoal fragment to the Late Bronze Age (Fig. 3). This corresponds well with the occurrence of Bronze Age settlements in the direct vicinity (Fig. 2; Bykowski, 1997). Generally, alluvial fan deposits are typically the result of high energy events that involve extreme precipitation as well as exposed and compacted soils resulting from human land use and a low vegetation cover density (Dreibrodt et al., 2010a). The Bronze Age onset of intensive human impact on the landscape development is typical for Central

Europe (Smolska, 2007; Schmitt et al., 2006; Dreibrodt et al., 2010b) and this region (Pawłowski et al., 2014; Zygmunt, 2009).

With the beginning of the pre-Roman Iron Age the study area belonged to the core settlement area of the Przeworsk Culture (Godłowski, 1985), which populated eastern Central Europe approximately between the late 3rd century BCE until the 5th century CE (Dąbrowska, 2003). For this period the dated sedimentological record (profile NAMY02, unit VII; profile NAMY01, unit V; Figs. 3 and 5) at Rychnów I shows a gradual expansion of local alluvial fan deposits. Together with colluvial deposits, dating to the Roman period in transect Rychnów II (profile RYCHNOW13, unit III; Fig. 7), these alluvial formations point to a continuous human impact on the landscape around the Rychnów site. This continuous impact is also supported by the local archaeological record in the vicinity of this site, reaching from the Bronze Age to the Medieval period (Fig. 2; Bykowski, 1997). Furthermore, the colluvial deposits at the Pielgrzymowice site (profile PIELW14, unit V; Fig. 10) in the immediate vicinity of a Przeworsk Culture iron smelting site, investigated in Thelemann et al. (2016), probably also originate from the period between the pre-Roman Iron Age and the Roman period. Due to the number of prehistoric iron slag sites, particularly in the vicinity of the Rychnów and Pielgrzymowice sites (Fig. 2), the correlative erosion events were probably linked to prehistoric settlement and iron smelting activities. However, the small scale of early iron smelting activities, further investigated at Pielgrzymowice, imply that these erosion events were more likely connected to deforestation for agricultural land use and a general demand for wood than to iron smelting (Thelemann et al., 2016).

In the Medieval period the study area is characterized by a number of settlement sites, representing a regional increase of human activities (Fig. 2; Bykowski, 1997). Medieval archives could be dated at Młokicie (profile NAMY04, Fig. 9) and Rychnów (profile RYCHNOW12, Fig. 5) but the distinctive post-depositional pedogenesis in the upper colluvial deposits at transect Rychnów II (profile RYCHNOW13, unit IV, Fig. 7) probably also point to an erosion event during the Medieval period.

During modern periods human-induced landscape changes particularly increased, as shown in the dated topsoils at Rychnów (profile NAMY01, unit VI; Figs. 3 and 5). Especially the past two-and-a-half centuries affected landscape development in terms of human-induced erosion events, due to the complete deforestation of the study area since or prior to 1780 (Orczewska, 2009) and the concomitant intensive agricultural usage. Furthermore, in modern periods the

area was affected by channel regulations and melioration measures (Fig. 11F; TK25, 1886-1938).

5. Conclusions

Our investigations showed that a mix of primary sedimentological explorations with ^{14}C -datings and secondary geological data, highly-resolved LiDAR data and archaeological records represent a powerful combination in order to reconstruct the Pleistocene and Holocene development of this rather uninvestigated landscape history, also involving early human impacts with an emphasis on the effects of iron production.

Since the last ice coverage during the Drenthe stadial of the Saalian complex, approx. 290-220 ka BP, the landscape history of the study area can be subdivided into six main phases: (A) During the last ice advance, coming from northwest, the eskers, which cover the northwestern plateaus of the study area, were deposited. (B) Subsequent to the ice retreat, the current course of the Widawa valley initially developed with (i) a southerly flow direction from the ice margin, followed by (ii) a turn to a westerly flow direction parallel to the ice marginal position. (C) Subsequently a wide braided river system accumulated glaciofluvial Drenthe deposits, which today are preserved as terraces along the Widawa valley. (D) As the area was situated in the south of the Warthe ice margin, approx. 220-170 ka BP, the intense glaciofluvial meltwater discharge induced a dramatic valley incision. Subsequently, glaciofluvial sediments of the Warthe stadial accumulated, which today remain as terraces along the Widawa valley, detected at Rychnów. (E) Before fluvial sediments deposited during the Weichselian glaciation, approx. 110-11.7 ka BP, the Widawa valley slightly further incised. In the upper reaches of the Widawa at Rychnów an anastomosing river system established. In the lower reaches relatively thick, often gravelly floodplain deposits accumulated during the Hengelo interstadial of the Weichselian glacial period, which are today preserved as Weichselian terraces at Lubska and Młokicie. (F) Prior to the accumulation of Holocene fluvial deposits, beginning approx. 11.7 ka BP, the Widawa valley further incised before several peat layers were formed in the anastomosing river system north of Namysłów. During the Holocene the anastomosing river system expanded to the lower reaches of the Widawa valley.

Initially during the Bronze Age, approx. 3.14 ± 0.21 ka BP, and more evidently during the Iron Age, approx. 2.54 ± 0.18 ka BP, human impact on the landscape became apparent, as seen in the sediment archives, particularly traceable in the alluvial fan and colluvial deposits

at Rychnów, but probably also verifiable in the colluvial deposits at Pielgrzymowice. These sediment archives indicate the beginning of intensified land use during the pre-Roman Iron Age and the Roman period and are spatially and temporally linked to the iron smelting activities of the Przeworsk culture. A more recent human impact on the landscape development is chronologically unresolved in the sediment archives investigated – apart from colluvial deposits dating to the Medieval period at transect Rychnów II. Nevertheless, in comparison to human-induced landscape changes at the beginning of iron smelting, it is expected that recent landscape impacts, in terms of deforestation, agriculture and melioration measures, such as water table drawdown and construction of channels, ditches and dams, have had a much more intense effect on the landscape development, in terms of erosion sensitivity and anthropogenic landscape overprinting.

The landscape of the study area has undergone major changes since the Drenthe ice advance. Focusing on locations related to prehistoric slag sites, it is possible to trace an early impact on the development of the landscape particularly during the pre-Roman Iron Age and the Roman period. Since then, human impact on the study area has given a new direction to the local landscape development.

Acknowledgements

This study was supported by the Cluster of Excellence TOPOI EXC 264 and the collaboration of our Topoi Research Group A-5 “Iron as a Raw Material”. We would like to thank our cooperation partners from the Archaeological Institute of the University of Wrocław, Prof. Dr. Artur Błażejowski, and the Museum of Archaeology Wrocław, Dr. Paweł Madera for their support in the field. Special thanks are dedicated to Prof. Dr. Michael Meyer and Dr. Enrico Lehnhardt from the Institute for Prehistoric Archaeology of the Freie Universität Berlin for their support in our common research project. Additionally we would also like to thank Dipl.-Geogr. Johanna Seidel and the students of the 2013 field campaign of the Institute of Geographical Sciences at the Freie Universität Berlin. We also thank René Hahn, Manuela Scholz and Michaela Scholz from the Institute of Geographical Sciences of the Freie Universität Berlin for their support in the geochemical laboratory. We would like to address our special thanks to the Department of Cultural Heritage Opole, Poland.

References

- Ad-Hoc-AG Boden, 2005. Bodenkundliche Kartieranleitung. 5th improved and extended Ed. (KA5). Bundesanstalt für Geowissenschaften und Rohstoffe (Ed.), Hannover, Germany. Schweizerbart'sche Verlagsbuchhandlung Stuttgart.
- AZP, since 1978. Archeologiczne Zdjęcie Polski (Polish Archaeological Record). Archaeological catalogue. Department of Cultural Heritage Opole, Poland.
- Bartczak, E., 1997. Geological detailed map, 1 : 50.000. Map sheet 0766 Namysłów. Polish Geological Institute, National Research Institute.
- Bausenwein, U., Gattinger, A., Langer, U., Embacher, A., Hartmann, H.-P., Sommer, M., Munch, J., Schlöter, M., 2008. Exploring soil microbial communities and soil organic matter: Variability and interactions in arable soils under minimum tillage practice. *Applied Soil Ecology* 40, 67-77.
- Bertrand, S., Huguen, K., Lamy, F., Stuut, J.-B., Torrejón, F., Lange, C., 2012. Precipitation as the main driver of Neoglacial fluctuations of Gualas glacier, Northern Patagonian Icefield. *Climate of the Past* 8, 1-16.
- Blättermann, M., Frechen, M., Gass, A., Hoelzmann, P., Parzinger, H., Schütt, B., 2012. Late Holocene landscape reconstruction in the Land of Seven Rivers, Kazakhstan. *Quaternary International* 251, 42-51.
- Blume, H.-P., Brümmer, G., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretschmar, R., Stahr, K., Wilke, B.-M., 2010. Scheffer/Schachtschabel Lehrbuch der Bodenkunde. 16th Ed. Spektrum-Springer, Heidelberg.
- Borgolte, M., 2002. Europa entdeckt seine Vielfalt 1050-1250. Handbuch der Geschichte Europas. Vol. 3. Eugen Ulmer Verlag, Stuttgart.
- Börner, A., 2007. Comparison of Quaternary stratigraphy used in Northeast-Germany and Poland. *Brandenburg. Geowiss. Beitr.* 14, 15-24.
- Borówka, R., Osadczuk, A., Witkowski, A., Wawrzyniak-Wydrowska, B., Duda, T., 2005. Late Glacial and Holocene depositional history in the eastern part of the Szczecin Lagoon (Great Lagoon) basin - NW Poland. *Quaternary International* 130, 87-96.
- Bronk Ramsey, C., Lee, S., 2013. Recent and Planned Developments of the Program OxCal. *Radiocarbon* 55, 720-730.
- Bykowski, K., 1997. Wyniki badań powierzchniowych na obszarze 80-35, Badania archeologiczne na Górnym Śląsku i ziemiach porganicznych w 1993 roku, 197-221.
- Cincio, Z., 1997. Geological detailed map, 1 : 50.000. Map sheet 0767 Rychtal. Polish Geological Institute, National Research Institute.
- Climate-data.org, 1982-2012. AmbiWeb GmbH. <http://en.climate-data.org/location/10308/> Last access 23.11.2015.
- CODGiK, 2013. Centralny Ośrodek Dokumentacji Geodezyjnej i Kartograficznej. Central Documentation Center for Geodesy and Cartography, Poland.
- Cohen, K., Gibbard, P., 2011. Global chronostratigraphical correlation table for the last 2.7 million years. Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy), Cambridge, England.
- Dabkowski, J., 2014. High potential of calcareous tufas for integrative multidisciplinary studies and prospects for archaeology in Europe. *Journal of Archaeological Science* 52, 72-83.

- Dąbrowska, T., 2003. Przeworsk-Kultur. In: Reallexikon der Germanischen Altertumskunde 23. De Gruyter Berlin, 540-567.
- Dean, W., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *Journal of Sedimentary Petrology* 44, 242–248.
- Dean, W., 2009. Holocene Record of Major and Trace Components in the Sediments of an Urban Impoundment on the Mississippi River: Lake Pepin, Minnesota and Wisconsin. USGS Open-File Report 1238, 1-13.
- Dreibrodt, S., Lubos, C., Terhorst, B., Damm, B., Bork, H.-R., 2010a. Historical soil erosion by water in Germany: Scales and archives, chronology, research perspectives. *Quaternary International* 222, 80-95.
- Dreibrodt, S., Lomax, J., Nelle, O., Lubos, C., Fischer, P., Mitusov, A., Reiss, S., Radtke, U., Nadeau, M., Meiert Grootes, P., Bork, H.-P., 2010b. Are mid-latitude slopes sensitive to climatic oscillations? Implications from an Early Holocene sequence of slope deposits and buried soils from eastern Germany. *Geomorphology* 122, 351-369.
- Engels, S., Helmens, K., Väiliranta, M., Brooks, S., Birks, H., 2010. Early Weichselian (MIS 5d and 5c) temperatures and environmental changes in northern Fennoscandia as recorded by chironomids and macroremains at Sokli, northeast Finland. *Boreas* 39, 689-704.
- Ford, T., Pedley, H., 1996. A review of tufa and travertine deposits of the world. *Earth-Science Reviews* 41, 117-175.
- Fuchs, M., Fischer, M., Reverman, R., 2010. Colluvial and alluvial sediment archives temporally resolved by OSL dating - Implications for reconstructing soil erosion. *Quaternary Geochronology* 5, 269-273.
- Godłowski, K., 1985. Przemiany kulturowe i osadnicze w południowej i środkowej Polsce w młodszym okresie przedrzymskim i w okresie rzymskim. *Prace Komisji Archeologicznej. Polska Akad. Nauk, Oddział w Krakowie* 23. Zakład Narodowy im. Ossolińskich, Wrocław.
- Goetz, H.-W., 2003. Europa im frühen Mittelalter 500 – 1050. *Handbuch der Geschichte Europas* 2. Ulmer Verlag, Stuttgart.
- Goudie, A., Viles, H., Penecost, A., 1993. The late-Holocene tufa decline in Europe. *The Holocene* 3, 181-196.
- Gozhik, P., Lindner, L., Marks, L., 2012. Late Early and early Middle Pleistocene limits of Scandinavian glaciations in Poland and Ukraine. *Quaternary International* 271, 31-37.
- Gradzinski, R., Baryła, J., Danowski, W., Doktor, M., Gmur, D., Gradzinski, M., Kedzior, A., Paszkowski, M., Soja, R., Zielinski, T., Zurek, S., 2000. Anastomosing System of the Upper Narwe River, NE Poland. *Annales Societatis Geologorum Poloniae* 70, 219-229.
- Griffiths, H., Pedly, H., 1995. Did changes in late Last Glacial and early Holocene atmospheric CO₂ concentrations control rates of tufa precipitation? *The Holocene* 5, 238-242.
- Gruszka, B., Morawski, W., Zielinski, T., 2012. Sedimentary record of a Pleistocene ice-sheet interlobate zone (NE Poland). *Geologos* 18, 65-81.
- Haberstroh, J., 2000. Germanische Funde der Kaiser- und Völkerwanderungszeit aus Oberfranken. *Materialhefte zur bayerischen Vorgeschichte. Bayerischen Landesamt für Denkmalpflege, Kallmünz*.

- Heiri, O., Lotter, A., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25, 101-110.
- Helbig, H., De Klerk, P., 2002. Befunde zur spätglazialen fluvial-limnischen Morphodynamik in kleinen Talungen Vorpommerns. *Eiszeitalter und Gegenwart - Quaternary Science Journal* 51, 51-66.
- Hickin, E., 1984. Vegetation and River Channel Dynamics. *Canadian Geographer* 2, 111-126.
- James, L., Harden, C., Clague, J., 2013. Geomorphology of Human Disturbances, Climate Change, and Hazards. *Treatise on Geomorphology. Reference Module in Earth Systems and Environmental Sciences* 13, 1-13.
- Jary, Z., 2009. Periglacial markers within the Late Pleistocene loess-palaeosol sequences in Poland and Western Ukraine. *Quaternary International* 198, 124-135.
- Joosten, I., Jansen, B., Kars, H., 1998. Geochemistry and the past: estimation of the output of a Germanic iron production site in the Netherlands. *Journal of Geochemical Exploration* 62, 129-137.
- Kaiser, K., Lorenz, S., Germer, S., Joschus, O., Küster, M., Libra, J., Bens, O., Hüttl, R., 2012. Late Quaternary evolution of rivers, lakes and peatlands in northeast Germany reflecting past climatic and human impact – an overview. *Quaternary Science Journal* 61, 103-132.
- Kittel, P., Muzolf, B., Płóciennik, M., Elias, S., Brooks, S., Lutyńska, M., Pawłowski, D., Stachowicz-Rybka, R., Wacnik, A., Okupny, D., Głab, Z., Mueller-Bieniek, A., 2014. A multi-proxy reconstruction from Lutomierske Koziowki, Central Poland, in the context of early modern hemp and flax processing. *Journal of Archaeological Science* 50, 318-337.
- Krajcarz, M., Cyrwek, K., Krajcarz, M., Mroczek, P., Sudoł, M., Szymanek, M., Tomek, T., Madeyska, T., 2015. Loess in a cave: Lithostratigraphic and correlative value of loess and loess-like layers in caves from the Krakow-Czestochowa Upland (Poland). *Quaternary International*, 1-18.
- Krzyszowski, D., Kuszell, T., 2007. Middle and Upper Weichselian Pleniglacial Fluvial Erosion and Sedimentation Phases in Southwestern Poland, and their Relationship to Scandinavian Ice Sheet Build-Up and Retreat. *Annales Societatis Geologorum Polaniae* 77, 17-38.
- Krzywicki, T., 2002. The maximum ice sheet limit of the Vistulian Glaciation in northeastern Poland and neighbouring areas. *Geological Quarterly* 46, 165-188.
- Kümmel, C., 2009. Ur- und frühgeschichtlicher Grabraub: Archäologische Interpretation und kulturanthropologische Erklärung. *Tübinger Schriften zur Ur- und Frühgeschichtlichen Archäologie* 9. Waxmann Verlag, Münster/München.
- Kuszell, T., Chmal, R., Słychan, K., 2007. Early Vistulian climate oscillations in the light of pollen analysis of deposits from Dziadowa Kłoda (Silesian Lowland, Poland). *Geological Quarterly* 51, 319-328.
- Kuttler, W., 2009. *Klimatologie*. Verlag Ferdinand Schöningh, Paderborn.
- KZGW, 2015. Krajowy Zarząd Gospodarki Wodnej, Polish National Department for Water Management. <http://mapa.kzgw.gov.pl/>, last access 10.11.2015.
- Leser, H., Stäblein, G., 1985. Legend of the geomorphological map 1 : 25.000 (GMK 25) – fifth version in the GMK priority program of the Deutsche Forschungsgemeinschaft. *Berliner Geographische Abhandlungen* 39, 61-89.

- Liedtke, H., 1981. Die Nordischen Vereisungen in Mitteleuropa, Forschungen zur Deutschen Landeskunde. Band 204. 2nd extended Ed. Zentrallausschuss der Deutschen Landeskunde, Selbstverlag. Trier.
- Lindner, L., Marks, L., 2008. Pleistocene Stratigraphy of Poland and its Correlation with Stratotype Sections in the Volhynian Upland (Ukraine). *Geochronometria* 31, 31-37.
- Litt, T., Behre, K.-E., Meyer, K.-D., Stephan, H.-J., Wansa, S., 2007. Stratigraphische Begriffe für das Quartär des norddeutschen Vereisungsgebietes, Eiszeit und Gegenwart - *Quaternary Science Journal* 56, 7-65.
- Maaß, K., Voigt, T., Gaupp, R., 2010. Äolische und fluviatile Sedimentation im Unteren Buntsandstein (Calvörde-Formation) Ost-Thüringens. *Beitr. Geol. Thüringen* 17, 169-199.
- Marks, L., 2012. Timing of the Late Vistulian (Weichselian) glacial phases in Poland. *Quaternary Science Reviews* 44, 81-88.
- Marks, L., Galazka, D., Woronko, B., in press. Climate, environment and stratigraphy of the last Pleistocene glacial stage in Poland. *Quaternary International*, 1-13.
- Morgan, R., 2005. Soil Erosion and Conservation. Third Edition. National Soil Resource Institute, Cranfield University. Blackwell Publishing, Blackwell Science company, Oxford.
- Munsell, 2000. Munsell Soil Color Charts. Revised Washable Edition. New York.
- Natural Earth data, 2013. Version 3.1.0. <http://www.naturalearthdata.com/>, last access 15.10.2013.
- North, M., 2007. Europa expandiert 1250 – 1500. *Handbuch der Geschichte Europas* 4. Ulmer Verlag, Stuttgart.
- Orczewska, A., 2009. Age and Origin of Forests in South-western Poland and their Importance for Ecological Studies in Man-dominated Landscapes. *Landscape Research* 34, 599-617.
- Orzechowski, S., 2002. Hutnictwo świętokrzyskie oraz inne centra i ośrodki starożytnej metalurgii żelaza na ziemiach polskich. *Kielce*, 159-165.
- Pawłowski, D., Milecka, K., Kittel, P., Woszczyk, M., Spychalski, W., 2014. Palaeoecological record of natural changes and human impact in a small river valley in Central Poland. *Quaternary International*, 1-17.
- Pelzer, F., 1991. Polen – Eine geographische Landeskunde. *Wissenschaftliche Länderkunden*, Band 36. Wissenschaftliche Buchgesellschaft, Darmstadt.
- Przybylak, R., Brázdil, R., Majorowicz, J., Kejna, M., 2010. The Polish Climate in the European Context: An Historical Overview. Springer Science+Business Media B.V.
- Puttkammer, T., 2012. Auf den Spuren der Germanen. Begleitband zur Wanderausstellung. Museum der Westlausitz, Kamenz.
- Ralska-Jasiewiczowa, M., 1983. Isopollen Maps for Poland: 0-11000 Years B.P. *New Phytologist* 94, 133-175.
- Raukas, A., Stankowski, W., 2005. Influence of sedimentological composition on OSL dating of glaciofluvial deposits: examples from Estonia. *Geological Quarterly* 49, 463-470.
- Reimer, P., Bard, E., Bayliss, A., Warren Beck, J., Blackwell, P., Bronk Ramsey, C., Buck, C., Cheng, H., Lawrence Edwards, R., Friedrich, M., Grootes, P., Guilderson, T., Hafliðason, H., Hajdas, I., Hatté, C., Heaton, T., Hoffmann, D., Hogg, A., Hughen, K., Kaiser, K., Kromer, B., Manning, S., Niu, M., Reimer, R., Richards, D., Marian Scott, E., Southon, J.,

- Staff, R., Turney, C., van der Plicht, J., 2013. Intcal13 and Marine13 Radiocarbon Age Calibration Curves 0-50,000 Years Cal BP. *Radiocarbon* 55, 1869-1887.
- Rössner, T., 1998. Die mitteleuropäische West-Ost-Achse Sachsen-Schlesien-Galizien. Institut für Länderkunde, Leipzig.
- Schmitt, A., Rodzik, J., Zglobicki, W., Russok, C., Dotterweich, M., Bork, H.-R., 2006. Time and scale of gully erosion in the Jedliczny Dol gully system, south-east Poland. *Catena* 68, 124-132.
- Schneider, S., Matthaei, A., Schlöffel, M., Meyer, C., Kronwald, M., Pint, A., Schütt, B., 2015. A geoarchaeological case study in the chora of Pergamon, western Turkey, to reconstruct the late Holocene landscape development and settlement history. *Quaternary International* 367, 62-76.
- Schütt, B., 2004. The chemistry of playa-lake-sediments as a tool for the reconstruction of Holocene environmental conditions – a case study from the central Ebro basin. In: Smykatz-Kloss, W., Felix-Henningsen, P. (Eds.), *Paleoecology of Quaternary drylands. Lecture Notes in Earth Science* 102, 5-30.
- Smolska, E., 2007. Development of gullies and sediment fans in last-glacial areas on the example of the Suwałki Lakeland (NE Poland). *Catena* 71, 122-131.
- Starkel, L., 1995. Reconstruction of hydrological changes between 7000 and 3000 BP in the upper and middle Vistula River Basin, Poland. *The Holocene* 5, 34-42.
- Starkel, L., Soja, R., Michczyńska, D., 2006. Past hydrological events reflected in Holocene history of Polish rivers. *Catena* 66, 24-33.
- Superson, J., Rodzik, J., Reder, J., Zglobicki, W., Klimowicz, Z., Franczak, Ł., 2015. Phases of alluvial fan development in a loess area, Lublin Upland, E Poland. *Quaternary International*, 1- 15.
- Thelemann, M., Lehnhardt, E., Bebermeier, W., Meyer, M., 2016. Iron, Humans and Landscape – Insights from a Micro-Region in the Widawa Catchment Area, Silesia. In: *Bridging the Gap – Integrated Approaches in Landscape Archaeology, eTopoi. Journal for Ancient Studies, Special Volume 4* (2015), 109-138.
- TK25, 1886-1938. Topographic map 1 : 25.000, plane-table sheets 4871 (Bernstadt, 1899), 4872 (Schmograu, 1886), 4971 (Lampersdorf, 1912) and 4972 (Namslau, 1938). *Preußische Landesaufnahme*.
- USGS, 2000. U.S. Geological Survey. SRTM-data set 1 Arc-Second Global. <http://earthexplorer.usgs.gov/>, last access 10.10.2015.
- Vandenberghe, J., 2002. The relation between climate and river processes, landforms and deposits during the Quaternary. *Quaternary International* 91, 17-23.
- Walanus, A., Nalepka, D., 2005. Wiek Rzeczywisty Granic Chronozon Wyznaczonych Wlatach Radiowęglowych. Roślinne ślady człowieka: Using plants to trace the activities of prehistoric people. *Botanical Guidebooks* 28. Polish Academy of Sciences, Kraków.
- Watters, J., Stanley, E., 2007. Stream channels in peatlands - The role of biological processes in controlling channel form. *Geomorphology* 89, 97-110.
- Wiatkowski, M., Rosik-Dukewska, C., Tyminski, T. 2010. Analysis of Water Management of the Michalice Reservoir in Relation to its Functions. *Ecological Chemistry and Engineering* 17, 1505-1516.

- Williams, R., Rennie, C., Brasington, J., Hicks, D., Vericat, D., 2015. Linking the spatial distribution of bed load transport to morphological change during high-flow events in a shallow braided river. *Journal of Geophysical Research: Earth Surface* 120, 604-622.
- Winnicki, J., 1997. Geological structure of the Trzebnica Hills in the light of new investigation. *Geological Quarterly* 41, 365-380.
- Wozniak, P., Czubla, P., 2015. The Late Weichselian glacial record in northern Poland: A new look at debris transport routes by the Fennoscandian Ice Sheet. *Quaternary International* 386, 3-17.
- Wysota, W., Chruscinska, A., Lankauf, K., Przegietka, K., Oczkowi, H., Szmanda, J., 2000. Chronostratigraphy of the vistulian deposits in the southern part of the Lower Vistula region (north Poland) in the light of TL dating. *Geologos* 5, 123-134.
- Zygmunt, E., 2009. Alluvial fans as an effect of long-term man–landscape interactions and moist climatic conditions: A case study from the Glubczyce Plateau, SW Poland. *Geomorphology* 108, 58-70.

5.4 Case study IV:

Geochemical analyses of charcoal piles and rectangular stoves at the Prehistoric Przeworsk iron smelting site Pielgrzymowice in Silesia, Poland

Unpublished work report

Keywords: Prehistoric iron smelting, Przeworsk culture, Environmental assessment, Paleo-environmental impacts

Abstract

The study site of Pielgrzymowice is situated in the Widawa catchment area, a tributary catchment area of the Oder River in northeastern Silesia, Poland. According to the Archaeological Record Poland, a nationwide archaeological survey conducted in Poland since 1978, this site is an iron slag site dedicated to the pre-Roman Iron Age and the Przeworsk culture. Approximately in the 2nd century BCE the technology of iron smelting was introduced to this region. During two archaeological field campaigns archaeological surveys, geomagnetic prospections as well as an excavation were conducted at this prehistoric site. In the context of these archaeological investigations also Pürckhauer transects and excavation sections were conducted and investigated in terms of chemical bulk parameters (phosphate, TOC, pH and selected major and trace elements) to complement and further characterize the archaeological findings with quantitative geochemical data and gain further information on the use and function of these structures. In the framework of this approach also the paleo-environmental impacts of early iron smelting activities in the immediate vicinity of these structures was examined in order to derive statements on small-scale landscape changes in the vicinity of the smelting site.

1. Introduction

The technology of iron smelting, whose history dates back to the 2nd millennium BCE coming from the territory of the Hittite culture, reached Central and northern Europe approximately in the 5th century BCE (Pleiner, 2000; Yalçın, 2000). Although many case studies have been conducted on the spreading of iron smelting in Europe, the current status of research greatly

varies between different regions (Bebermeier et al., accepted). Particularly, the beginning of early iron smelting in the Przeworsk culture – a European Iron Age culture – requires further research, as it might represent a missing link between the Latène culture and Iron Age cultures of northeastern Europe. The Przeworsk culture settled in eastern Central Europe approximately between the late 3rd century BCE and the 5th century CE (Dąbrowska, 2003). According to the Archaeological Record Poland (AZP, since 1978) the region of Silesia, as the central dissemination area of this culture, shows numerous prehistoric iron slag sites, which are located in the floodplains of the Oder River and its tributaries. A cluster of those slag sites is situated in the Widawa catchment area in southwestern Poland (Fig. 1).

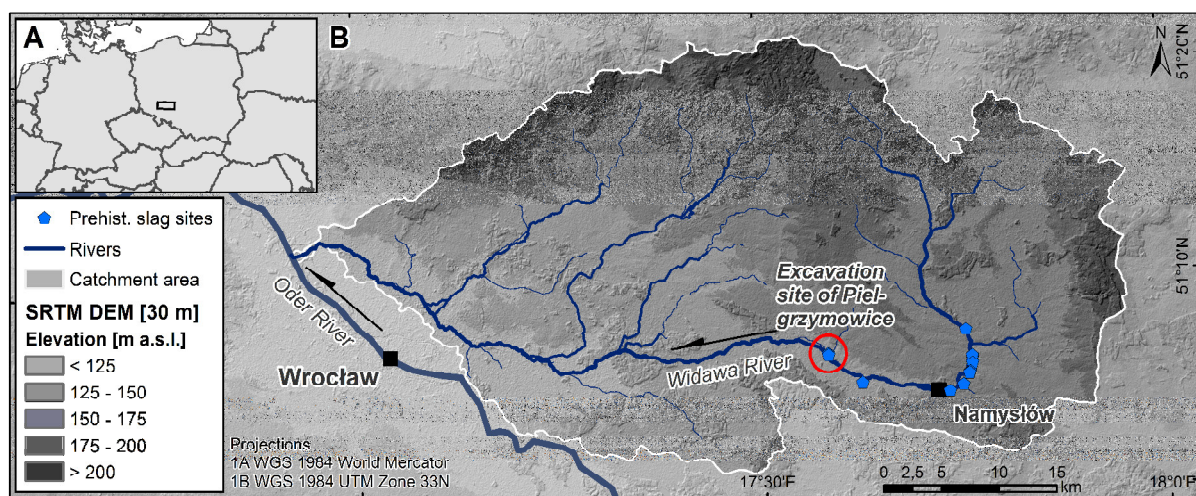


Fig. 1A. Location of the study area in eastern Central Europe; 1B. Location of the Pielgrzymowice excavation site in the Widawa catchment area.

Data: Fig. 1A: Country borders from Natural Earth Data (2013), extension of the region of Silesia from Global Administrative Areas (2013); Fig. 1B: Digital elevation model with a horizontal resolution of 30 m (1-arc second) from USGS (2000) SRTM data; rivers from Natural Earth Data (2013) and KZGW (2015); Widawa catchment area from KZGW (2015).

In an interdisciplinary research project within the Cluster of Excellence Topoi archaeological excavations, sedimentological investigations and geomagnetic prospections were conducted and commissioned at a prehistoric iron slag site near the village of Pielgrzymowice by the Institute of Prehistoric Archaeology and the Institute of Geographical Sciences, Freie Universität Berlin (Thelemann et al., 2016). The research questions the following geomorphological and geochemical investigations in the context of the archaeological excavation are, (i) what do the geomagnetic anomalies represent in the context of the slag site of Pielgrzymowice, (ii) is a paleo-environmental impact detectable in the sediment archives of these anomalies and (iii) what conclusions can be drawn on relief changes subsequently to the prehistoric activities at this site?

2. Excavation site Pielgrzymowice

Based on the archaeological catalogue of the AZP (since 1978), which assigns early iron smelting activities during the pre-Roman Iron Age to the vicinity of Pielgrzymowice, a field campaign was conducted in 2013, including geomagnetic prospections and archaeological surveys. During these surveys most iron slags were detected at the archaeological site of Pielgrzymowice 5 (Fig. 2; Thelemann et al., 2016). Therefore, an archaeological excavation at the location of selected clusters of geomagnetic anomalies was conducted at this site in 2014, consisting of five trenches. In trenches 3 and 4 remains of two prehistoric iron smelting furnaces with a very big hearth, dedicated to the Przeworsk culture, were detected (Appendix D – Case study IV, Fig. A.1; Thelemann et al., 2016). At the geomagnetic anomalies in trench 3 and 5 four organic-rich archaeological findings, two of them of rectangular shape, were detected (Appendix D – Case study IV, Fig. A.2). Furthermore, housing remains were excavated in trenches 1 and 2 (Fig. 2; Thelemann et al., 2016).

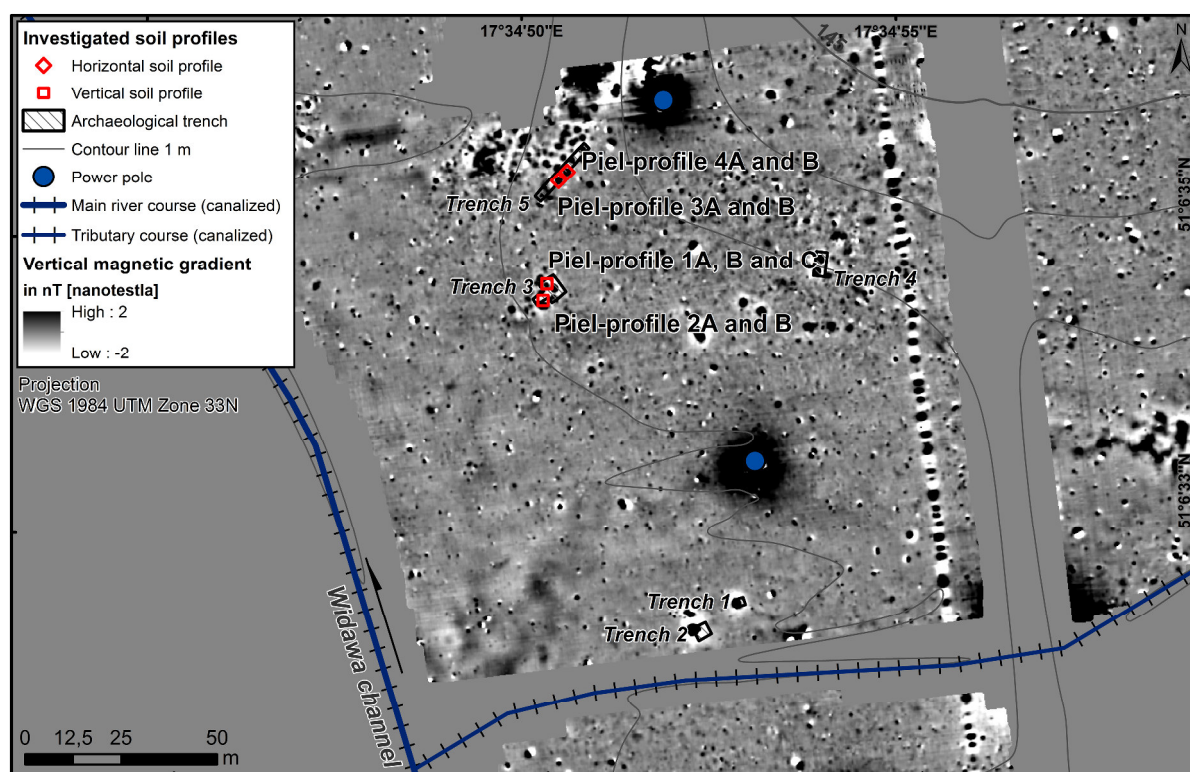


Fig. 2. Geomagnetic prospections and archaeological trenches with excavation sections at Pielgrzymowice 5.

Data: Rivers from KZGW (2015); contour lines from GODGiK (2013) LiDAR DEM with 1 m horizontal resolution; geomagnetic radar data produced by Eastern Atlas in 2014.

3. Methods

During the archaeological surveys two orthogonal, 1 m deep transects of 6 and 10 Pürckhauer drillings (P-NS and P-OW; Fig. 3) were conducted in an area showing a cluster of geomagnetic anomalies (Fig. 2). For these drillings phosphate spot tests (Gundlach, 1961) after Feigl (1960) were applied for depths of 33, 53, 73 and 93 cm below surface (b.s.). For this test about 2 g of soil material were placed on filter paper and reacted with ammonium molybdate solution for 30 seconds. Subsequently ascorbic acid was used as a reducing agent of the molybdenum and the blue color of the resulting phosphate molybdate acid indicates the amount of phosphate in the soil sample (Eidt, 1973; Gundlach, 1961). The resulting reaction was divided into 5 classes: I (no phosphate content), II, III, IV and V (very high phosphate content) (Wallin et al., 2008).

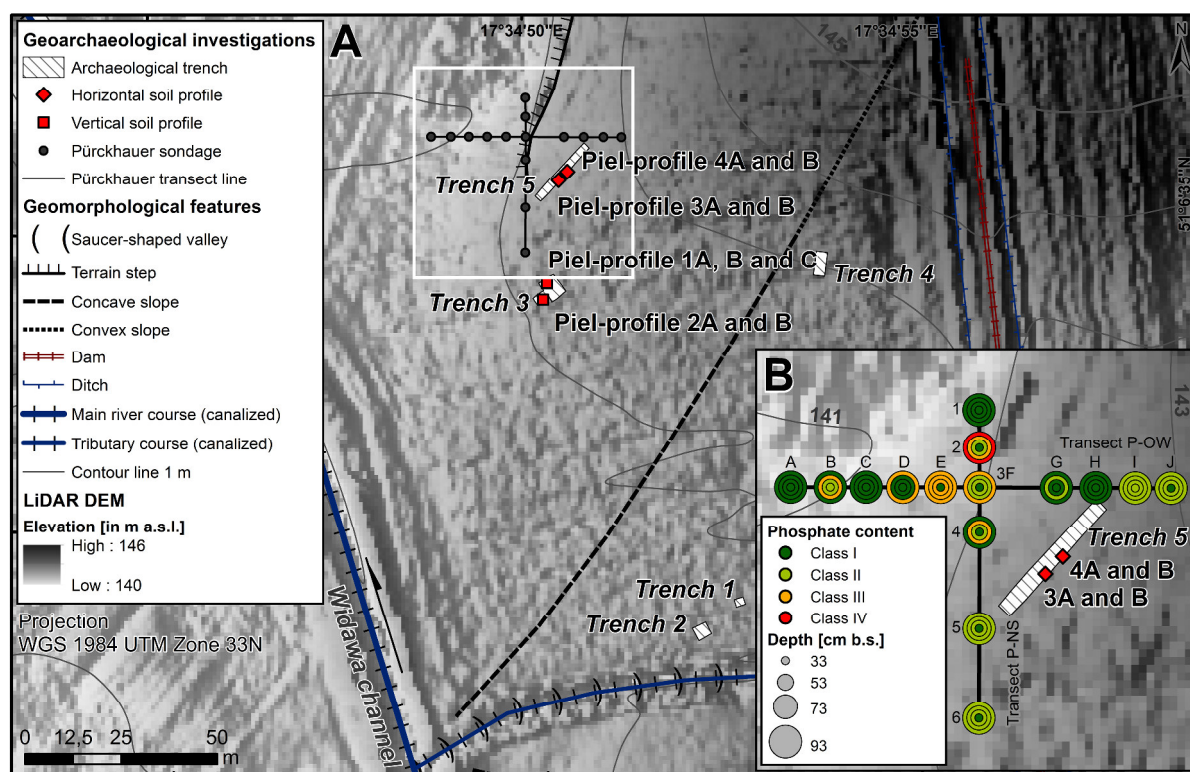


Fig. 3A. Pürckhauer sondages, archaeological trenches with excavation sections at the site of Pielgrzymowice 5. 3B. Results of phosphate spot tests in the Pürckhauer sondages 73 and 93 cm b.s. with horizontal excavation sections.

Data: Rivers from KZGW (2015); contour lines and hillshade from GODGiK (2013) LiDAR DEM with 1 m horizontal resolution; phosphate content classes according to Wallin et al. (2008).

As a part of the archaeological excavation at the study site of Pielgrzymowice in 2014 two vertical (Piel-profiles 1A, B, C and 2A, B) and two horizontal excavation sections (Piel-profiles 3A, B and 4A, B) were exposed in trenches 3 and 5, which are situated in the northern central part of the study site (Fig. 3). In order to complement and further characterize

the archaeological findings with quantitative geochemical data to gain further information on the use and function of these structures these sections were recorded according to the German Pedological Mapping Guide (Ad-Hoc-AG Boden, 2005), the carbonate content was estimated using 9.9 % HCl and soil samples were taken in the soil profiles every 5 to 10 cm (Appendix D – Case study IV, Table A.1).

The samples were analyzed in the laboratory of the Institute of Geographical Sciences of the Freie Universität Berlin. For all 96 samples the following parameters were determined according to the laboratory standards: (i) gravel content, (ii) water content, (iii) pH value, (iv) total carbon (TC) content, (v) loss on ignition at 550 °C (LOI550), (vi) phosphate content (after Feigl, 1960) and (vii) major and trace element concentrations. The total inorganic carbon was not determined as the samples completely lack CaCO₃ tested with 9.9 % HCl. Therefore, the TOC also represents the TC content. The pH values were measured using a stationary HANNA instruments HI 221 Calibration Check Microprocessor pH Meter. The TC was measured using a LECO TruSpec CHN+S Elemental Analyzer. The LOI550 was determined according to Dean (1974) and Heiri et al. (2001) at 550 °C using a Thermo Scientific M110 Muffle Furnace. From the LOI550 also the TOC was estimated by applying the factor of $1 \cdot 1.72^{-1}$ (Blume et al., 2010). The phosphate contents were again estimated semi-quantitatively by exerting the phosphate spot tests (Gundlach, 1961). The major element concentrations (calcium, iron, potassium, magnesium, sodium, phosphorus and manganese) and the trace element concentrations (cadmium, chrome, copper, nickel, lead, strontium and zinc) were determined using inductively coupled plasma optical emission spectrometry (ICP-OES) with an ICP-OES Spectrometer Optima 2100 DV from Perkin Elmer.

4. Results

4.1 Phosphate contents at the Pürckhauer transects

The results of the phosphate analyses according to Gundlach (1961) of the soils along the Pürckhauer transects show distinctly increased phosphate contents in the center of the geomagnetic anomaly: In depths of 73 and 93 cm b.s. pürckhauer drillings B, D E, 3F and 4 (Fig. 3) show phosphate contents of up to class III according to Wallin et al., 2008 and

drilling 2 shows contents up to class IV (Fig. 3). In contrast depths of 33 and 53 cm b.s. of all drillings show hardly traceable phosphate contents and apart from drilling E only reach phosphate classes I and II (Fig. 3).

4.2 Excavation sections at trench 3

The two investigated vertical excavation sections documented in trench 3 (Fig. 3) revealed two archaeological findings with a horizontal diameter of 2.0 m each. Archaeological finding 1 was investigated through the vertical Piel-profiles 1A, B and C (Fig. 4) and archaeological finding 2 was investigated in Piel-profiles 2A and B (Fig. 5).

At finding 1 the bases of the profiles 1A, B and C below 40 to 60 cm b.s. are characterized by an organic free, carbonate free, sandy subsurface horizon [C] with oxidation features. These are at profiles 1A and B in a depth of c. 55 cm b.s. followed by an organic-rich, carbonate-free sandy anthropogenic layer I [M I] with stone infillings. In a depth of c. 45 cm b.s. these layers are again followed by another organic-rich, carbonate-free sandy anthropogenic horizon II [M II] without stone infillings. In contrast profile 1C in a depth of c. 40 cm b.s. is characterized by an organic-rich, carbonate free, sandy relictic topsoil [rA]. The following plough horizon [Ap] between c. 30 cm b.s. and the surface is not part of the profile as it was removed during the archaeological excavation (Fig. 4).

At finding 2 the bases of the profiles 2A and B below 45 to 75 cm b.s. are characterized by an organic free, carbonate free, sandy subsurface horizon [C] with oxidation features. This is at profile 2A in a depth of c. 75 cm b.s. followed by a very organic-rich, carbonate-free sandy anthropogenic horizon I [M I]. Subsequently, in a depth of 45 cm b.s. another very organic-rich, carbonate-free sandy anthropogenic horizon II [M II] again with stone infillings is followed. At profile 2B the depth of c. 50 cm b.s. is characterized by an organic-rich, carbonate free, sandy relictic topsoil [rA]. The following layer between c. 30 cm b.s. and the surface shows an organic-rich, carbonate-free loamy sandy plough horizon [Ap] (Fig. 5).

In accordance with the field results the laboratory results of both findings (profiles 1A, 1B and 2A) show a clear distinction to the neighboring comparative profiles 1C and 2B, as the TC and major and trace element contents are significantly higher at the findings. At profiles 1A and B, particularly the TC, iron, calcium, phosphorus as well as zinc, copper and strontium are increased in depths between 35 and 60 cm b.s. (Fig. 4), while at profile 2A particularly the TC and iron as well as zinc and copper contents are significantly higher in depth between 40 and 80 cm b.s. (Fig. 5), compared to the respective comparative profiles 1C

and 2B. Additionally, both profiles at finding 2 are characterized by increased lead and chrome contents with decreasing depth compared to finding 1 (Fig. 5). The increased TC and element contents and the differences inside and outside of the findings are overlain by the tendency that these contents are generally increasing with decreasing depth. In contrast the pH values show only very slight variations (between 5.4 and 6.4) and varying tendencies with decreasing depth (Figs. 4 and 5). All profiles show phosphate contents of class I (none) and II (Wallin et al., 2008; Appendix D – Case study IV, Table A.1). Apart from the often slightly underestimated TOC from the LOI550 and the clear peak in soil profile 1A the estimated TOC and the measured TC (LECO) coincide relatively well.

4.3 Excavation sections at trench 5

The two investigated horizontal excavation sections recorded in trench 5 (Fig. 3) showed two archaeological findings with a horizontal diameter of ca. 0.9 m each. Archaeological finding 3 was investigated through the vertical Piel-profiles 3A and B (Fig. 6) and archaeological finding 4 was investigated in Piel-profiles 4A and B (Fig. 7). The structure of findings 3 and 4 is very similar as they represent rectangular shaped distinctly humous archaeological findings with stone infillings in the subsoil in depths of c. 30 cm b.s.

The laboratory results of the TC and major and trace element contents also display a relatively clear geochemical distinction of the finding, as these contents are by trend increasing to the center. At profiles 3A and B particularly the TC and iron as well as zinc, chrome and strontium contents significantly increase to the center (Fig. 6), while at profile 4A particularly the iron as well as chrome and at profile 4B particularly the TC, iron as well as zinc contents significantly accumulate towards the center (Fig. 7). Nevertheless, the highest values, in terms of TC, iron and phosphorus contents, were often detected at the edges of the archaeological findings and particularly for iron there is a clear peak at the edges. With very slight variations (between 5.7 and 6.1) the pH values decrease towards the center of the finding (Figs. 6 and 7). The samples display phosphate contents of class II and III with highest values particularly at the edge of the finding (Appendix D – Case study IV, Table A.1). In comparison to the TC (LECO), the TOC (LOI550) is constantly overestimated and even shows a distinct peak in profile 4B that was not measured in the TC.

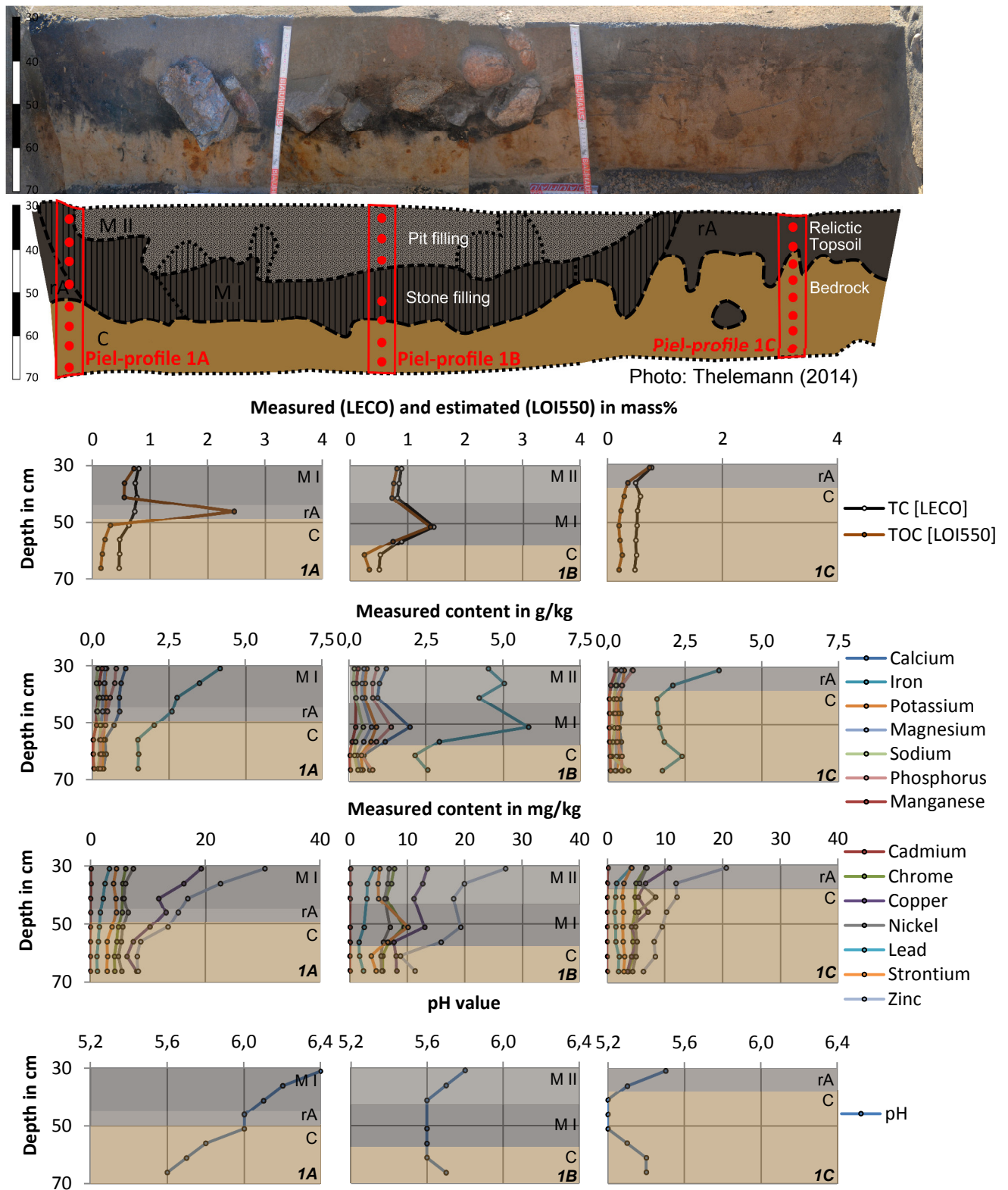


Fig. 4. Geochemical characterization of archaeological finding 1 at vertical Piel-profiles 1A, B and C.

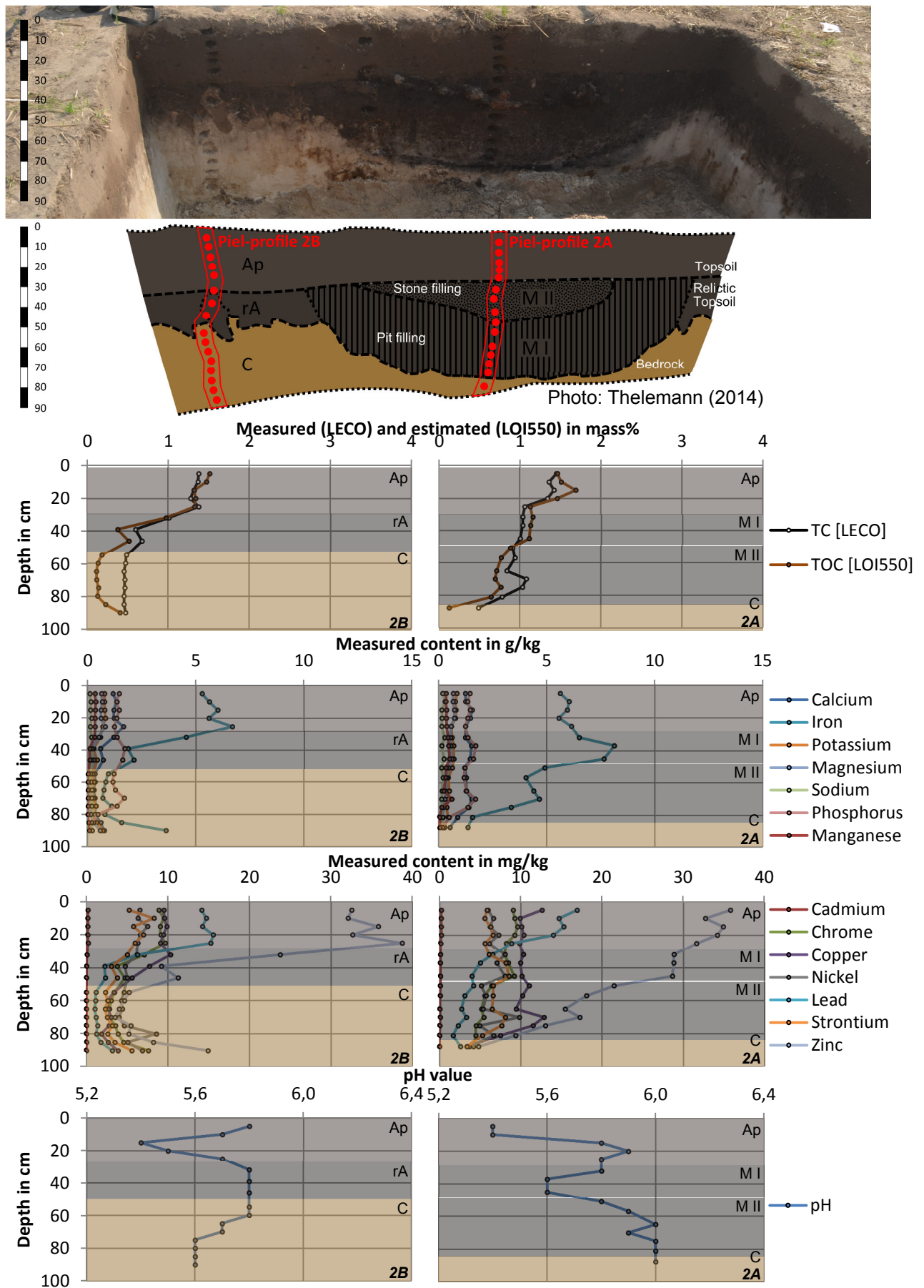


Fig. 5. Geochemical characterization of archaeological finding 2 at vertical Piel-profiles 2A and B.



Photo: Thelemann (2014)

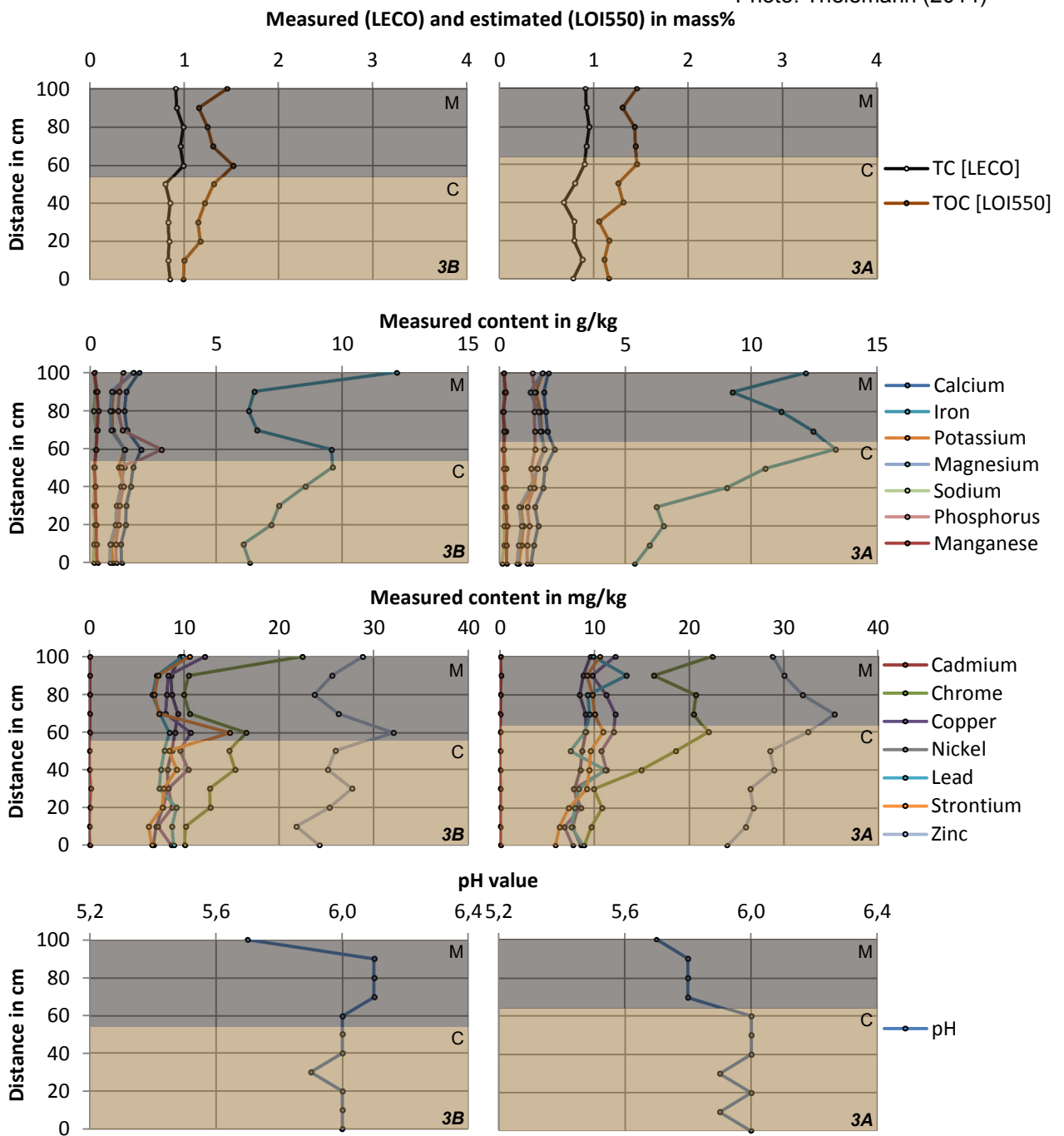


Fig. 6. Geochemical characterization of archaeological finding 3 at horizontal Piel-profiles 3A and B.



Photo: Thelemann (2014)

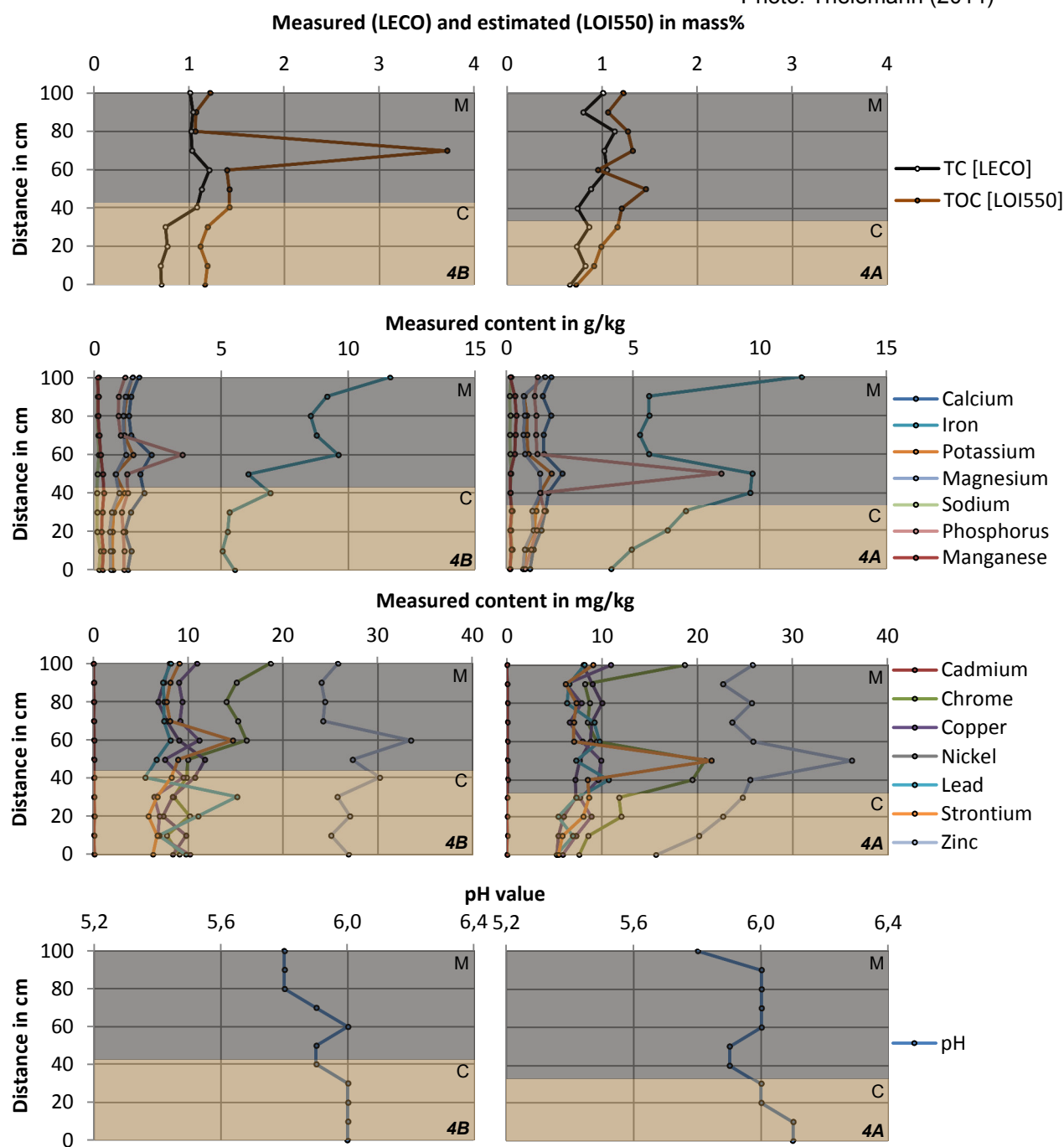


Fig. 7. Geochemical characterization of archaeological finding 4 at horizontal Piel-profiles 4A and B.

5. Discussion

5.1 Phosphate contents at the Pürckhauer transects

The increased phosphate contents in depths of 73 and 93 cm b.s. in the center of the examined geomagnetic anomaly imply that this anomaly represents an archaeological feature as increased soil phosphate contents are a proxy for fecal input (Craddock et al., 1985). The method is based on the strong immobility of phosphate and the circumstance that human and animal fecal input of phosphate extends those of nature and even heavy agricultural fertilization (Eidt, 1973). The reached quantities of phosphate in this archaeological finding point to a settlement feature with a direct human (or animal husbandry) induced phosphate input (Eidt, 1973) rather than an immediate iron smelting place. The distinctly lower phosphate contents in the layers above 60 cm b.s. point to a subsequent colluvial cover of the cultural layers in the settlement context. Nevertheless, the phosphate spot test has to be used and interpreted carefully as it is only a method to semi-quantitatively determine phosphate without differentiating the kind and source of the phosphate.

5.2 Excavation sections at trench 3

Also the increased TC and element contents as well as the stone fillings detected in the archaeological findings 1 and 2 at trench 3 in the immediate spatial context of the smelting furnaces (Appendix D – Case study IV, Fig. A.1; Thelemann et al., 2016) clearly point to anthropogenic features (Hoelzmann et al., 2012). Similar structures to the findings 1 and 2 in layering and shape at Karlskron and Manderbach (Germany) as well as Novoklinove (Ukraine) were described by Pleiner (2000) as charcoal piles. As it is characteristic, also at Pielgrzymowice these structures additionally show a horizontal diameter of 2 m and a depth of approximately 0.4 m as well as slag-pit furnaces in the immediate vicinity (Pleiner, 2000). Therefore, the investigated findings 1 and 2 are interpreted as remains of charcoal piles. Due to the need for charcoal during the iron smelting with a bloomery furnace, those piles are a very common structure in the vicinity of smelting sites from the beginning of the Iron Age to medieval periods (Thiele, 2010; Pleiner, 2000). According to Pleiner (2000) the identified sunken charcoal piles at Pielgrzymowice represent the typical pile type in Silesia. For the charcoal production often stones were used to cover the bottom of the pile, before the wood was piled up and finally sealed with clay (Pleiner, 2000). The structures at Pielgrzymowice represent the relicts of the sunken pile base with remaining charcoal and stone layers. These layers are characterized by a distinct TOC peak from LOI550 in profiles 1A and B (Fig. 4).

As this peak does not occur in the TC content in profile 1A a measuring error of the LOI550 is probable. It is particular for the charcoal pile 2 (profile 2A) – in contrast to pile 1 – that the sandy pit filling is overlain by stone fillings, which represents an important difference in these structures. Furthermore, a distinct TOC peak was not detected in the remains of pile 2 – but in the overlain current plough horizon. It is suggested that the upper part of pile 2, with possibly higher TOC contents, has already been truncated by the subsequent tillage farming at this location. The relative depth of the pile remains points to an at least 10 cm thick coverage by colluvial deposits.

Geochemically, in comparison to the values in the immediate vicinity of these charcoal piles (profiles 1C and 2B) the significantly increased TC and most of the major and trace element concentrations within the range of the piles (profiles 1A, B and 2A; Figs. 4 and 5) very well represent the extents of the investigated charcoal piles. Particularly the increased TC, iron, calcium, phosphorus, zinc, strontium, chrome and copper contents represent geochemical components that characterize these structures. The TC increase towards the center of these anthropogenic structures is a common feature as it was also identified in regular pit fillings of the Przeworsk culture in the Harz-Foreland by Hoelzmann et al. (2012). Although the comparative profiles 1C and 2B do not necessarily represent a natural context, as they are still set in the immediate vicinity of the archaeological finding, these findings are emerging distinctly in the geochemical results (Figs. 4 and 5). Particularly the iron, calcium, zinc and copper contents seem to be relatively high, if these piles were only used for producing charcoal from wood. Furthermore, the general increase of element contents with decreasing depth, which is also detectable at the profiles 1C and 2B additionally points to contaminations through a subsequent sediment and element input. Exceptional are the increasing lead and chrome contents with and without find context in the profiles 2A and B, which is only detectable at pile 2. Nevertheless, the measured element contents of the charcoal piles only show a relative increase as these values, e.g. in terms of cadmium, lead, nickel, copper and zinc, are more than 450 times below German soil boundary values for tillage farming (BBodSchV, 1999).

5.3 Excavation sections at trench 5

The increased TC and element contents, the stone fillings as well as the clear rectangular shape detected in the archaeological findings 3 and 4 at trench 5 also point to prehistoric settlement features. These rectangular structures are in configuration and shape typical for the Przeworsk culture and represent stove holes as relicts of rectangular hearths (Madyda-

Legutko et al., 2006; Roczkalski and Włodarczak, 2009; Thelemann et al., 2016). Similar to trench 3, these structures are truncated by subsequent tillage farming in a depth of 30 cm b.s. Again the relative depth of the stove remains points to an at least 10 cm thick coverage by colluvial deposits.

In comparison to the values outside of these stove remains, the geochemical parameters of the significantly increased TC and most of the major and trace element concentrations in the center of these remains (profiles 3A, 3B, 4A and B; Figs. 6 and 7) also very well represent the extents of these remains. Particularly the increased TC, iron, phosphorus, calcium, zinc, chrome, strontium and copper contents and the pH values represent parameters that characterize these structures. In this sense the geochemical parameters of the stove remains are similar the regular pit fillings investigated by Hoelzmann et al. (2012), as the pH values decrease towards the centers of these structures. Furthermore, particular for these stoves is the increase of the TC, iron, zinc and chrome contents, predominantly at the edges of these structures. Also in the context of these profiles it has to be mentioned that the comparative profile sections outside of the stove remains do not necessarily represent a natural context, as they are still set in the immediate vicinity these stoves (Figs. 6 and 7). Although the function of these stoves is not reconstructed in the framework of this investigation, it can be stated that the increased TC and element contents as well as the often decreasing pH values closer to the center represent a paleo-environmental impact, which originates from the usage of the stoves. Increased cadmium and lead contents would point to iron smelting activities rather than combusted ash remains of burned wood (Hillel et al., 2004). Since increased cadmium and lead contents are not the case at the stoves, it is assumed that iron smelting activities, such as post-processing of the bloom, were not conducted at these stoves. As stated for the charcoal piles also the soil element contents at the stoves, e.g. in terms of cadmium, lead, nickel, copper and zinc, are more than 450 times below German soil boundary values for tillage farming (BBodSchV, 1999).

6. Conclusions

The five investigated geomagnetic anomalies at the Przeworsk iron smelting site of Pielgrzymowice, which were investigated by geomagnetic and archaeological surveys as well as an archaeological excavation in 2014 (Thelemann et al., 2016), can be identified as (i) a settlement feature with a direct human (or animal husbandry) induced phosphate input, (ii) two sunken charcoal piles and (iii) two rectangular stoves. The configuration of these pile

and stove remains is typical for Silesia (Pleiner, 2000) and the Przeworsk culture (Madyda-Legutko et al., 2006; Roczkalski and Włodarczak, 2009), respectively.

A slight paleo-environmental impact in the investigated geochemical parameters was detected in all investigated profiles. The settlement feature investigated through Pürckhauer transects shows increased phosphate contents, particularly in and below depths of 73 cm b.s. The extents of the pile and stove remains are well characterized by the geochemical composition of the respective soil layers. Particularly the TC and iron contents, but also the zinc, chrome and copper contents are distinctly increased in the center of these structures. Nevertheless, in absolute values the measured element contents are very uncritical – if not negligible – as these concentrations in terms of cadmium, lead, nickel, copper and zinc lie more than 450 times below German soil boundary values for tillage farming (BBodSchV, 1999).

Similar to investigations by Hoelzmann et al. (2012) for the Harz-Foreland (Central Germany), the landscape at the study site has undergone distinct changes. In case of Pielgrzymowice these changes occurred since the last human activities at this smelting site during the Roman period. Due to a severe colluvial mass movement anthropogenic features are lying extensively 10 to 60 cm below the present surface. Through these colluvial layers the archaeological and geochemical archives of this smelting site were protected from being fully destroyed, as the site is currently used for agriculture, which enabled the preservation of these evidences on early iron smelting attempts in the Przeworsk culture.

Acknowledgements

This study was supported by the Cluster of Excellence Exc264 Topoi and the collaboration of our Topoi Research Group A-5 “Iron as a Raw Material”. Fieldwork was made possible only by the help and setting in the study area. Therefore, we would like to thank our cooperation partners from the Archaeological Institute of the University of Wrocław, Prof. Dr. Artur Błażejowski, and the Museum of Archaeology Wrocław, Dr. Paweł Madera. Additionally, we would also like to thank Dipl.-Geogr. Johanna Seidel and the students of the field campaigns 2013 and 2014 of the Institute of Geographical Sciences respectively the Institute of Prehistoric Archaeology of the Freie Universität Berlin. Thanks also to Mrs. Manuela Scholz and Michaela Scholz from the Institute of Geographical Sciences of the Freie Universität Berlin for their support in the geochemical laboratory. We would like to address our special thanks to the Department of Cultural Heritage Opole, Poland. Particularly, we would like to thank Prof. Dr. Meyer and Dr. Enrico Lehnhardt from the Institute of Prehistoric Archaeology

of the Freie Universität for the close collaboration and the exchange of information during and subsequently to the fieldwork.

References

- Ad-Hoc-AG Boden, 2005. Bodenkundliche Kartieranleitung. 5th improved and extended Ed. (KA5). Bundesanstalt für Geowissenschaften und Rohstoffe (Ed.), Hannover, Germany. Schweizerbart'sche Verlagsbuchhandlung Stuttgart.
- AZP, since 1978. Archeologiczne Zdjęcie Polski (Polish Archaeological Record). Archaeological catalogue. Department of Cultural Heritage Opole, Poland.
- BBodSchV, 1999. Bundes-Bodenschutz- und Altlastenverordnung, Anhang 2. Bundesgesetzblatt. Bundesministerium der Justiz und für Verbraucherschutz. https://www.gesetze-im-internet.de/bbodschv/anhang_2.html, last access 22.01.2016.
- Bebermeier, W., Brumlich, M., Cordani, V., de Vincenzo, S., Eilbracht, H., Hofmann, A., Klinger, J., Knitter, D., Lehnhardt, E., Meyer, M., Schmid, S., Schütt, B., Thelemann, M., Ullrich, B., Wemhoff, M., accepted. The coming of iron in a comparative perspective. *eTopoi*.
- Blume, H.-P., Brümmer, G., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K., Wilke, B.-M., 2010. Scheffer/Schachtschabel Lehrbuch der Bodenkunde. 16th Ed. Spektrum-Springer, Heidelberg.
- CODGiK, 2013. Centralny Ośrodek Dokumentacji Geodezyjnej i Kartograficznej. Central Documentation Center for Geodesy and Cartography, Poland.
- Craddock, P., Gurney, D., Pryor F., Hughes, M., 1985. The Application of Phosphate Analysis to the Location and Interpretation of Archaeological Sites, *Archaeological Journal* 142, 361-376.
- Dąbrowska, T., 2003. Przeworsk-Kultur. In: *Reallexikon der Germanischen Altertumskunde* 23. De Gruyter Berlin, 540-567.
- Dean, W., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *Journal of Sedimentary Petrology* 44, 242-248.
- Eidt, R., 1973. A Rapid Chemical Field Test for Archaeological Site Surveying. *American Antiquity* 38, 206-210.
- Feigl, F., 1960. Tüpfelanalyse. Anorganischer Teil. 4th Ed. Vol. 1. Akademische Verlagsgesellschaft M.B.H. Frankfurt am Main.
- Global Administrative Areas, 2013. Collaboration of the Universities of California, Berkeley and Davis. <http://www.gadm.org/>, last access 15.10.2013.
- Gundlach, H., 1961. Tüpfelmethode auf Phosphat, angewandt in prähistorischer Forschung (als Feldmethode). *Mikrochimica Acta* 5, 735-737.
- Heiri, O., Lotter, A., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25, 101-110.
- Hillel, D., Rosenzweig, C., Powlson, D., Scow, K., Singer, M., Sparks, D., 2004. *Encyclopedia of Soils in the Environment*. Vol. 3. Academic Press, 1st Ed. New York.

- Hoelzmann, P., Rauchfuß, B., Ullrich, B., Bebermeier, W., Kaufmann, G., Schütt, B., Meyer, M., 2012. Coupling of Geomorphological, Geophysical, Geochemical and Archaeological Spatial Data for a Study of the Interface of the Latène and Przeworsk Cultures in NE Germany. *eTopoi. Journal for Ancient Studies*, Special Vol. 3, 399-403.
- KZGW, 2015. Krajowy Zarząd Gospodarki Wodnej, Polish National Department for Water Management. <http://mapa.kzgw.gov.pl/>, last access 10.11.2015.
- Madyda-Legutko, R., Pohorska-Kleja, E., Rodzińska-Nowak, J., 2006. Osada z okresu rzymskiego w Pakoszówce, stan. 1, pow. Sanok. *Rocznik Przemyski. Archeologia* 42/2, 69-84.
- Natural Earth data, 2013. Version 3.1.0. <http://www.naturalearthdata.com/>, last access 15.10.2013.
- Pleiner, R., 2000. Iron in Archaeology – The European Bloomery Smelters. *Archeologický ústav AV ČR*, Prague.
- Roczalski, B., Włodarczak, P., 2009. Badania wykopaliskowe przeprowadzone w latach 2005-2006 na stanowisku 4 w Łysokaniach oraz na stanowisku 33 w Brzeziu. *Raport 2005-2006*. Warszawa, 359-369.
- Thelemann, M., Lehnhardt, E., Bebermeier, W., Meyer, M., 2016. Iron, Humans and Landscape – Insights from a Micro-Region in the Widawa Catchment Area, Silesia. In: *Bridging the Gap – Integrated Approaches in Landscape Archaeology*, *eTopoi. Journal for Ancient Studies*, Special Volume 4 (2015), 109-138.
- Thiele, A., 2010. Smelting experiments in the early medieval fajszi-type bloomery and the metallurgy of iron bloom. *Mechanical Engineering* 54/2, 99-104.
- USGS, 2000. U.S. Geological Survey. SRTM-data set 1 Arc-Second Global. <http://earthexplorer.usgs.gov/>, last access 10.10.2015.
- Wallin, P., Österholm, I., Österholm, S., Solsvik, R., 2008. Phosphates and bones: An analysis of the courtyard of marae Manunu, Huahine, Society Islands, French Polynesia. *Terra Australis* 29, 423-434.
- Yalçın, Ü., 2000. Zur Technologie der frühen Eisenverhüttung. *Arbeits- und Forschungsberichte zur Sächsischen Bodendenkmalpflege* 42, 307-316.

6. Concluding remarks

6.1 The relevance of the environment and landscape setting for early iron smelting

Apart from socio-cultural and technological prerequisites the introduction of early iron smelting to the study area required certain environment and landscape settings, involving the availability of iron ore, wood, clay, water and possibly wheat chaff and fluxing agents, in order to enable a locally independent iron production. This production would have not been possible without the provision of the appropriate material basis. Apart from iron ore, considerations on the resource potential in case study I (section 5.1) implied no scarcity of the required resources. Due to the geological setting of the Pleistocene Old Drift landscape of Lower Silesia, without iron gangue minerals of geological rock formations (Bartczak, 1997; Cincio, 1997), the provision of local raw iron was solely depending on the availability of post-sedimentary formed bog iron ores. The distribution of iron and manganese contents in water samples from different receiving waters in the study area, as an indicator for favorable conditions for the bog iron ore formation, revealed increased contents in the vicinity of the modern Michalice Reservoir (section 5.1). Also in case study II (section 5.2) it was shown that the presently detected ore deposits are typically situated at the margins of the flatter lowlands along the Widawa floodplain, showing highest iron contents in the vicinity of this reservoir. As these distribution patterns show a strong correlation with the immediate cluster of known local prehistoric iron slag sites, a distinct connection between the natural and cultural settings in terms of the resource situation on bog iron ores and the designated smelting sites is indicated. Among other factors that influenced the selection of these locations for early iron smelting, such as water accessibility, this outcome underlines the meaning of particularly the ore and its distribution for early iron smelters. An evaluation of the quality of utilized prehistoric ores on the basis of local iron slag finds points to equivalent iron contents compared to other neighboring centers for early iron smelting from similar studies in Poland (Domanski, 1972; Hensel, 1986). Nevertheless, due to large-scale deforestation, at least since 1780 (Orczewska, 2009), intensive agricultural usage and extensive melioration measures during modern times, as discussed in case study I, the present bog iron ore deposits represent only relicts of the former quality and distribution and a complete evaluation of the prehistoric ore inventory is hardly possible. In order to further assess whether the study area represented a particularly favorable location for smeltable bog iron ores compared to neighboring regions, as the local cluster of prehistoric slag sites

indicates (AZP, since 1978), a more extended investigation is required. This should involve further investigations of the quality and distribution of the bog iron ore and slag inventory at more sites in the study area also involving neighboring regions.

6.2 Impacts of early iron smelting on the landscape development and environment

Apart from naturally induced landscape changes during the Pleistocene and Holocene, that greatly modified the topography and nature of the landscape in the study area (section 5.3), human impacts on the landscape are extensive but often dedicated to an agricultural usage during the Modern period. First human-induced landscape changes, which were detected in dated alluvial and colluvial sediment archives in the vicinity of the prehistoric settlement and slag sites at Rychnów, become evident during the Bronze Age and distinctly increased in several phases during the pre-Roman Iron Age and the early Roman period. Also colluvial deposits at the iron smelting site of Pielgrzymowice point to human-induced landscape changes of the pre-Roman Iron Age and the early Roman period as suggested by excavated and dated settlement remains of these periods at this site (section 5.1). Through these sediment archives the beginning of intensified land use can be particularly assigned to the pre-Roman Iron Age. However, this intensification is not necessarily directly linked to iron smelting but can also be linked to agricultural activities of the Przeworsk culture. On the micro-scale at Pielgrzymowice, as presented in case study IV (section 5.4), additionally an environmental impact was detected in terms of increased geochemical parameters in the remains of excavated charcoal piles and rectangular stoves typical for the Przeworsk culture. Particularly the charcoal piles, which were located in the immediate vicinity of an excavated bloomery furnace of the Przeworsk culture, can be set in the direct context of iron smelting activities. But due to the characteristics of bog iron ores and the geogenic parent material of the study area, the reached heavy metal contents have to be generally regarded as very uncritical, as boundary values for tillage farming were not reached. Nevertheless, through the investigated archives a distinct human-induced small-scale impact on the environment and the landscape could be parallelized to early iron smelting activities.

6.3 Project synthesis of archaeological and geographical outcomes

As a landscape archaeological synthesis, subsequently to earliest human-induced landscape changes during the Bronze Age, the activities of the Przeworsk culture had a distinctly increased impact on depositional alluvial fan activities in the vicinity of a pre-Roman Iron

Age site. However, this impact is not necessarily connected to early iron smelting activities. Even though the Widawa valley contains a cluster of Przeworsk slag sites, no evidence could be found from an archaeological point of view for any early iron smelting activities prior to the Roman period (section 5.1). Accordingly, the only bloomery furnaces identified at the iron smelting site of Pielgrzymowice date to the Roman period and represent a further advanced type with a very big hearth (sections 5.1 and 5.4). From an archaeological perspective, being situated in the area of the Amber Road (Wielowiejski, 1980), a delayed introduction of iron smelting is assumed and explained by trade relations and exchange processes between the Baltic Sea in the north and the Latène culture in the south, which possibly enabled iron imports and diminished the necessity for self-sufficient iron mining. While the space for early iron production was mainly determined by the local availability of the necessary resources, the moment when this technology was introduced is primarily dependent on the socio-economic as well as the technological setting. A relatively late beginning of local smelting attempts in the study area, compared to other European Iron Age cultures, e.g. the Jastorf culture in western Central Europe (Brumlich et al., 2012), could be supported by the relatively high reducible efficiency (Charlton et al., 2010) derived from the chemical composition of the local iron slags (section, 5.2). Anyhow, compared to the sediments from the pre-Roman Iron Age, a further increased geomorphological activity during the Roman period – as it would be expectable from a later introduction of iron smelting activities – could not be proven in the investigated sediment archives of the study area (section 5.3). Whether or not this technology was introduced comparatively late to the study region, a lack of local ore deposits or other resources would be no sufficient explanation, due to our considerations on the resource inventory and the number of confirmed slag and ore sites (sections 5.1 and 5.2). However, for a conclusive statement on the period when iron smelting activities were introduced to the Widawa valley, excavations of further local iron slag sites, as suggested in section 6.1, are inevitable.

References

- Ad-Hoc-AG Boden, 2005. Bodenkundliche Kartieranleitung. 5th improved and extended Ed. (KA5). Bundesanstalt für Geowissenschaften und Rohstoffe (Ed.), Hannover, Germany. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.
- Ammann, A., 2007. Inductively coupled plasma mass spectrometry (ICP MS): a versatile tool. *Journal of Mass Spectrometry* 42, 419-427.
- AZP, since 1978. Archeologiczne Zdjęcie Polski (Polish Archaeological Record). Archaeological catalogue. Department of Cultural Heritage Opole, Poland.
- Banning, A., 2008. Bog Iron Ores and their Potential Role in Arsenic Dynamics: An Overview and a "Paleo Example". *English Life Science* 8, 641-649.
- Barker, G., Bintliff, J., 1999. Geoarchaeology in Mediterranean Landscape Archaeology: Concluding Comments. In: Leveau, P., Walsh, K. (Ed.). *Methodological issues in Mediterranean landscape archaeology*. Oxbow Books, Oxford.
- Bartczak, E., 1997. Geological detailed map, 1 : 50 000. Map sheet 0766 Namysłów. Polish Geological Institute, National Research Institute.
- Bartington Instruments, 2008. Operation Manual for MS2 Magnetic Susceptibility System. Bartington Instruments Limited, Oxford.
- Bebermeier, W., Hoelzmann, P., Meyer, M., Schimpf, S., Schütt, B., Wetzel, M., 2009: Die Siedlungsgeschichte des Südharzvorlandes. In: *Fundiert. Das Wissenschaftsmagazin der Freien Universität Berlin*, 1, 34-39.
- Bebermeier, W., Schütt, B., 2011. Geoarchaeology – A New Discipline. *Die Erde* 142/3, 209-212.
- Bebermeier, W., Brumlich, M., Cordani, V., de Vincenzo, S., Eilbracht, H., Hofmann, A., Klinger, J., Knitter, D., Lehnhardt, E., Meyer, M., Schmid, S., Schütt, B., Thelemann, M., Ullrich, B., Wemhoff, M., accepted. The coming of iron in a comparative perspective. *eTopoi*.
- Bell, M., Walker, M., 2005. Late Quaternary Environmental Change – Physical and Human Perspectives. 2nd Ed. Pearson Education Limited.
- Berking, J., Meister, J., Burkart, U., Schott, M., Kaufmann, G., Schütt, B., 2011. Geoarchaeological Methods for Landscape Reconstruction at the Excavation Site of Naga, Central Sudan. *Die Erde* 142, 289-313.
- Bertrand, S., Huguen, K., Lamy, F., Stuut, J.-B., Torrejón, F., Lange, C., 2012. Precipitation as the main driver of Neoglacial fluctuations of Gualas glacier, Northern Patagonian Icefield. *Climate of the Past* 8, 1-16.
- Beuselinck, L., Govers, G., Poesen, J., Degraer, G., Froyen, L., 1998. Grain-size analysis by laser diffractometry: comparison with the sieve-pipette method. *Catena* 32, 193-208.
- Bielenin, K. 1974. *Starożytne górnictwo i hutnictwo żelaza w Górach Świętokrzyskich*, Warszawa-Kraków, Państwowe Wydawnictwo Naukowe.
- Bielenin, K., Suliga, I., 2008. The Ancient Slag-Pit Furnace and the Reduction Process in the Light of a New Archaeological Concept and Metallurgical Research. *Metallurgy and Foundry Engineering* 34, 53-78.

- Blakelock, E., Martín-Torres, M., Veldhuijzen, H., Young, T., 2009. Slag inclusions in iron objects and the quest for provenance: an experiment. *Journal of Archaeological Science* 36, 1745-1757.
- Blättermann, M., Frechen, M., Gass, A., Hoelzmann, P., Parzinger, H., Schütt, B., 2012. Late Holocene landscape reconstruction in the Land of Seven Rivers, Kazakhstan. *Quaternary International* 251, 42-51.
- Blume, H.-P., Brümmer, G., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K., Wilke, B.-M., 2010. Scheffer/Schachtschabel Lehrbuch der Bodenkunde. 16th Ed. Spektrum-Springer, Heidelberg.
- Blume, H.-P., Stahr, K., Leinweber, P., 2011. Bodenkundliches Praktikum. 3rd Ed. Spektrum-Springer, Heidelberg.
- Börner, A., 2007. Comparison of Quaternary stratigraphy used in Northeast-Germany and Poland. *Brandenburgische Geowissenschaftliche Beiträge* 14, 15-24.
- Borgolte, M., 2002. Europa entdeckt seine Vielfalt 1050-1250. *Handbuch der Geschichte Europas*. Vol. 3. Eugen Ulmer Verlag, Stuttgart.
- Bradley, R., 1999. Paleoclimatology – Reconstructing Climates of the Quaternary. 2nd Ed. *International Geophysics Series*, 68. Elsevier Academic Press, San Diego, London.
- Brauns, M., Schwab, R., Gassmann, G., Wieland, G., Pernicka, E., 2013. Provenance of Iron Age iron in southern Germany: a new approach. *Journal of Archaeological Science* 40, 841-849.
- Bronk Ramsey, C., Lee, S., 2013. Recent and Planned Developments of the Program OxCal. *Radiocarbon* 55, 720-730.
- Brown, A., 2001. Alluvial Geoarchaeology – Floodplain archaeology and environmental change. *Cambridge Manuals in Archaeology*. Cambridge University Press, New York.
- Brown, A., 2008. Geoarchaeology, the four dimensional (4D) fluvial matrix and climatic causality. *Geomorphology* 101, 278-297.
- Brückner, H., Vött, A., 2008. Geoarchäologie – eine interdisziplinäre Wissenschaft par excellence. In: Kulke, E., Popp, H., Umgang mit Risiken. Katastrophen – Destabilisierung – Sicherheit.
- Brumlich, M., Meyer, M., Lychatz, B., 2012. Archäologische und archäometallurgische Untersuchungen zur latènezeitlichen Eisenverhüttung im nördlichen Mitteleuropa. *Prähistorische Zeitschrift* 87, 433-473.
- Buchwald, F., Wivel, H., 1998. Slag Analysis as a Method for the Characterization and Provenancing of Ancient Iron Objects. *Materials Characterization* 40, 73-96.
- Buchwald, F., 2005. Iron and Steel in Ancient Times. The Royal Dan. Academy of Science and Letters. Viborg.
- Burdukiewicz, J., 2003. Lower Palaeolithic sites with small artefacts in Poland. In: Burdukiewicz, J., Ronen, A. (Eds.). *Lower Palaeolithic Small Tools in Europe and the Levant*. *British Archaeological Reports* 1115, 65-92.
- Bykowski, K., 1997. Wyniki badań powierzchniowych na obszarze 80-35, Badania archeologiczne na Górnym Śląsku i ziemiach porganicznych w 1993 roku, 197-221.
- Canti, M., Huisman, D., 2015. Scientific advances in geoarchaeology during the last twenty years. *Journal of Archaeological Science* 56, 96-108.

- Cardarelli, F., 2008. *Materials Handbook: A Concise Desktop Reference*. 2nd Ed. Springer-Verlag, London.
- Charlton, M., Crew, P., Rehren, T., Shennan, S., 2010. Explaining the evolution of ironmaking recipes – An example from northwest Wales. *Journal of Archaeological Science* 29, 352-367.
- Charlton, M., Blakelock, E., Martín-Torres, M., Young, T., 2012. Investigating the production provenance of iron artifacts with multivariate methods. *Journal of Archaeological Science* 39, 2280-2293.
- Cincio, Z., 1997. Geological detailed map, 1 : 50 000. Map sheet 0767 Rychtal. Polish Geological Institute, National Research Institute.
- Climate-data Krązkowy, 1982-2012. Climate-data.org. AmbiWeb GmbH. <http://de.climate-data.org/location/88559/>, last access 23.11.2015.
- Climate-data Namysłów, 1982-2012. Climate-data.org. AmbiWeb GmbH. <http://de.climate-data.org/location/10308/>, last access 23.11.2015.
- Climate-data Opole, 1982-2012. Climate-data.org. AmbiWeb GmbH. <http://en.climate-data.org/location/1332/>, last access 23.11.2015.
- Climate-data Wrocław, 1982-2012. Climate-data.org. AmbiWeb GmbH. <http://de.climate-data.org/location/4531/>, last access 23.11.2015.
- CODGiK, 2013. Centralny Ośrodek Dokumentacji Geodezyjnej i Kartograficznej. Central Documentation Center for Geodesy and Cartography, Poland.
- Crew, P., 2011. Crew, P., Charlton, M., Dillmann, P., Fluzin, P., Salter, C., Truffaut, E., 2011. Cast iron from a bloomery furnace, in: Hošek, J., Cleere, H., Mihok, L. (Eds.), *The Archaeometallurgy of Iron – Recent Developments in Archaeological and Scientific Research*. Prague, 237-262.
- Dąbrowska, T., 2003. Przeworsk-Kultur. In: *Reallexikon der Germanischen Altertumskunde* 23. De Gruyter, Berlin, 540-567.
- Dadlez, R., Marek, S., Pokorski, J., 2000. Geological Map of Poland without Cainozoic deposits. 1 : 1000 000. Ministerstwo Srdowiska. Polish Geological Institute, National Research Institute, Warszawa.
- Dean, W., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *Journal of Sedimentary Petrology* 44, 242-248.
- Dean, W., 2009. Holocene Record of Major and Trace Components in the Sediments of an Urban Impoundment on the Mississippi River: Lake Pepin, Minnesota and Wisconsin. USGS Open-File Report 1238, 1-13.
- Degryse, P., Schneider, J., Muchez, P., 2009. Combined Pb-Sr isotopic analysis in provenancing late Roman iron raw materials in the territory of Sagalassos (SW Turkey). *Archaeological Anthropological Science* 1, 155-159.
- De Vries, J., Vrebos, B., 2002. Quantification of infinitely thick specimens by XRF analysis. In: Van Grieken, R., Markowicz, A. (Eds.). *Handbook of X-Ray Spectrometry*, 2nd revised and expanded Ed. Marcel Dekker, New York, Basel, 341-406.
- Domanski, G., 1972. Stanowisko Hutnicze I Osady Z Tarchalic, Pow. Wołów, Stan. 1. *Sprawozdania Archeologiczne*, t. XXIV, 391-438.

- Dotterweich, M., 2013. The history of human-induced soil erosion: Geomorphic legacies, early descriptions and research, and the development of soil conservation – A global synopsis. *Geomorphology* 201, 1-34.
- Draganits, E., Doneus, M., Gansum, T., Gustavsen, L., Nau, E., Tønning, C., Trinks, I., Neubauer, W., 2015. The late Nordic Iron Age and Viking Age royal burial site of Borre in Norway: ALS- and GPR-based landscape reconstruction and harbour location at an uplifting coastal area. *Quaternary International* 367, 96-110.
- Driese, S., 2009. Paleosols, Pre-Quaternary. In: Gornitz, V. (Ed.). *Encyclopedia of Paleoclimatology and Ancient Environments*. Encyclopedia of Earth Sciences Series. Springer Science+Business Media B.V., New York.
- Eidt, R., 1973. A Rapid Chemical Field Test for Archaeological Site Surveying. *American Antiquity* 38, 206-210.
- Evans, J., 2003. *Environmental Archaeology and the Social Order*. Routledge. London and New York.
- Evenstad, O., 1801. *Praktische Abhandlung von den Sumpf- und Morast-Eisensteinen in Norwegen und von der Methode solche in so genannten Bauer- oder Blaseöfen in Eisen und Stahl zu verwandeln*. Dieterichsche Buchhandlung, Göttingen.
- Fairbridge, R., 2009. History of Palaeoclimatology. In: Gornitz, V. (Ed.). *Encyclopedia of Paleoclimatology and Ancient Environments*. Encyclopedia of Earth Sciences Series. Springer Science+Business Media B.V., New York.
- Feigl, F., 1960. *Tüpfelanalyse. Anorganischer Teil*. 4th Ed. Vol. 1. Akademische Verlagsgesellschaft M.B.H., Frankfurt am Main.
- Fleming, A., 2006. Post-processual Landscape Archaeology: a Critique. *Cambridge Archaeological Journal* 16, 267-280.
- French, C., 2003. *Geoarchaeology in Action – Studies in soil micromorphology and landscape evolution*. Routledge. London and New York.
- Fuchs, M., Zöller, L., 2006. Geoarchäologie aus geomorphologischer Sicht – Eine konzeptionelle Betrachtung. *Erdkunde* 60, 139-146.
- Garner, J., 2011. Der latènezeitliche Verhüttungsplatz in Siegen-Niederschelden "Wartestraße". *METALLA* (Bochum), 1-148.
- Gassmann, G., 2005. *Forschungen zur keltischen Eisenerzverhüttung in Südwestdeutschland. Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg* 92, Theiss, Stuttgart.
- Gassmann G., Rösch, M., Wiland, G., 2012. Das Neuenburger Erzrevier im Nordschwarzwald als Wirtschaftsraum während der Späthallstatt- und Frühlatènezeit. *Germania, Anzeiger der Römisch-Germanischen Kommission des Deutschen Archäologischen Institute* 84, 273-306.
- Gebhardt, H., Glaser, R., Radtke, U., Reuber, P., 2011. *Geographie – Physische Geographie und Humangeographie*. 2nd Ed. Spektrum Akademischer Verlag, Heidelberg.
- Geofabrik, 2015. Geofabrik GmbH Karlsruhe. <http://download.geofabrik.de/europe/poland/opolskie.html>, last access 23.11.2015.
- Global Administrative Areas, 2013. Collaboration of the Universities of California, Berkeley and Davis. <http://www.gadm.org/>, last access 15.10.2013.
- Godłowski, K., 1965. Remarks on the Development of Przeworsk Culture Settlement in Upper Silesia. *Archaeologia Polonia* VIII, 37-65.

- Godłowski, K., 1985. Przemiany kulturowe i osadnicze w południowej i środkowej Polsce w młodszym okresie przedrzymskim i w okresie rzymskim. Prace Komisji Archeologicznej. Polska Akad. Nauk, Oddział w Krakowie 23. Zakład Narodowy im. Ossolińskich, Wrocław.
- Goetz, H.-W., 2003. Europa im frühen Mittelalter 500 – 1050. Handbuch der Geschichte Europas 2. Ulmer Verlag, Stuttgart.
- Goldberg, P., Macphail, R., 2006. Practical and Theoretical Geoarchaeology. Blackwell Publishing.
- Graupner, A., 1982. Raseneisenstein in Niedersachsen. Entstehung, Vorkommen, Zusammensetzung und Verwendung. Forschungen zur niedersächsischen Landeskunde 118. Kommissionsverlag Göttinger Tageblatt, Göttingen.
- Greene, K., 1995. Archaeology – An Introduction. 3rd Ed. Fully Revised. Routledge. B.T.Batsford Ltd.
- Gundlach, H., 1961. Tüpfelmethode auf Phosphat, angewandt in prähistorischer Forschung (als Feldmethode). Mikrochimica Acta 5, 735-737.
- Haberstroh, J., 2000. Germanische Funde der Kaiser- und Völkerwanderungszeit aus Oberfranken. Materialhefte zur bayerischen Vorgeschichte. Bayerischen Landesamt für Denkmalpflege, Kallmünz.
- Harrison, A., Cattani, I., Turfa, J., 2010. Metallurgy, environmental pollution and the decline of Etruscan civilization. Environmental Science and Pollution Research 17, 165-180.
- Heimann, R., Kreher, U., Spazier, I., Wetzel, G., 2001. Mineralogical and Chemical Investigations of Bloomery Slags from Prehistoric (8th Century BC to 4th Century AD) Iron Production Sites in Upper and Lower Lusatia, Germany. Archaeometry 43, 227-252.
- Heiri, O., Lotter, A., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology 25, 101-110.
- Hensel, Z., 1986. Z Badan Nad Technologia Otrzymywania Zelaza Na Terenie Mazowieckiego Ośrodka Metalurgicznego. Archeologia Polski. TOM XXXI. Zeszyt 1, 31-90.
- Hergarten, S., Robl, J., Stüwe, K., 2014. Extracting topographic swath profiles across curved geometric features. Earth Surface Dynamics 2, 97-104.
- Herz, N., Garrison, E., 1998. Geological Methods for Archaeology. Oxford University Press. New York.
- Hirsch, F., Schneider, A., Nicolay, A., Błaszkievicz, M., Kordowski, J., Noryskiewicz, A., Tyszkowski, S., Raab, A., Raab, T., 2015. Late Quaternary landscape development at the margin of the Pomeranian phase (MIS 2) near Lake Wygonin (Northern Poland). Catena 124, 28-44.
- Hoelzmann, P., Rauchfuß, B., Ullrich, B., Bebermeier, W., Kaufmann, G., Schütt, B., Meyer, M., 2012. Coupling of Geomorphological, Geophysical, Geochemical and Archaeological Spatial Data for a Study of the Interface of the Latène and Przeworsk Cultures in NE Germany. eTopoi. Journal for Ancient Studies, Special Vol. 3, 399-403.
- Holliday, V., 2004. Soils in Archaeological Research. Oxford University Press.
- Hošek, J., Cleere, H., Mihok, L. (Eds.), 2011. The Archaeometallurgy of Iron. Recent Developments in Archaeological and Scientific Research. Institute of Archaeology of the ASCR. Helvetica and Tempora, Prague.

- Hou, X., Jones, B., 2000. Inductively Coupled Plasma/Optical Emission Spectrometry. *Encyclopedia of Analytical Chemistry*, 9468-9485.
- Iles, L., 2014. The exploitation of manganese-rich 'ore' to smelt iron in Mwenge, western Uganda, from the mid second millennium AD. *Journal of Archaeological Science* 49, 423-441.
- Ivanišević, V., Bugarski, I., 2015. Landscape reconstruction in the Middle Danube Roman Limes: case studies from Lederata and Smorna. In: Ivanišević, V., Veljanovski, T., Cowley, D., Kierszys, G., Bugarski, I. (Eds.). *Recovering Lost Landscapes*. Aerial Archaeology Research Group.
- James, L., Harden, C., Clague, J., 2013. Geomorphology of Human Disturbances, Climate Change, and Hazards. *Treatise on Geomorphology*. Reference Module in Earth Systems and Environmental Sciences 13, 1-13.
- Jenkins, R., 1999. *X-Ray Fluorescence Spectrometry*, 2nd Ed. John Wiley & Sons, New York.
- Joosten, I., Jansen, B., Kars, H., 1998. Geochemistry and the past: estimation of the output of a Germanic iron production site in the Netherlands. *Journal of Geochemical Exploration* 62, 129-137.
- Jouttijärvi, A., 2013. The Iron Slag from Toftanes. In: Toftanes – A Viking Age Farmstead in the Faroe Islands. *Acta Archaeologica* 84, 123-126.
- Joyner, L., 2005. Geoarchaeology. In: Selley, R., Cocks, L., Plimer, I. (Eds.) *Encyclopedia of Geology*. 1st Ed. Elsevier Ltd., Oxford.
- Kaczorek, D., Sommer, M., 2003. Micromorphology, chemistry, and mineralogy of bog iron ores from Poland. *Catena* 54, 393-402.
- Kaczorek, D., Sommer, M., Andruschkewitsch, I., Oktaba, L., Czerwinski, Z., Stahr, K., 2004. A comparative micromorphological and chemical study of "Raseneisenstein" (bog iron ore) and "Ortstein". *Geoderma* 121, 83-94.
- Kaczorek, D., Brümmer, G., Sommer, M., 2005. Content and Binding Forms of Heavy Metals, Aluminium and Phosphorus in Bog Iron Ores from Poland. *Journal of Environmental Quality* 38, 1109-1119.
- Kalis, A., Merkt, J., Wunderlich, J. 2003. Environmental changes during the Holocene climatic optimum in central Europe – human impact and natural causes. *Quaternary Science Reviews* 22, 33-79.
- Kasperek, R., Mokwa, M., Wiatkowski, M., 2013. Modelling of Pollution Transport with Sediment on the Example of the Widawa River. *Archives of Environmental Protection* 39, 29-43.
- Kempa, O., Hełdak, M., 2011. Delineation of Shoreline on the Basis of the Widawa and Dobra Rivers in Wrocław. *Contemporary Problems of Management and Environmental Protection, Issues of Landscape Conservation and Water Management in Rural Areas* 7, 91-101.
- Killick, D., Fenn, T., 2012. Archaeometallurgy: The Study of Preindustrial Mining and Metallurgy. *Geological Quarterly* 162-163, 133-140.
- Klimek, K., 2010. Past and present interaction between the catchment and the valley floor: Upper Osoblaha basin, NE Sudetes slope and foreland. *Quaternary International* 220, 112-121.

- Kluiwing, S. Guttman-Bond, E., 2012. LAC 2010: First International Landscape Archaeology Conference. In: Kluiwing, S. Guttman-Bond, E. (Eds.). *Landscape Archaeology between Art and Science – From a Multi- to an Interdisciplinary Approach*. Landscape and Heritage Series. Amsterdam University Press, Amsterdam.
- Kluiwing, S., Lehmkuhl, F., Schütt, B., 2012. Landscape archaeology at the LAC2010 conference. *Quaternary International* 251, 1-6.
- Kosmala, G., 2013. Geographical characteristics of Silesia. In: Harc, L., Wiszewski, P., Żerelik, R. (Eds.), *Cuius regio? Ideological and Territorial Cohesion of the Historical Region of Silesia (c. 1000-2000)*. Vol. 1. Uniwersytet Wrocławski. Publishing House, Wrocław.
- Krambach, M., unpublished. QGIS-Swath Profile Plugin for Creation of Generalized Profiles. <http://krambach.de/swath-profile/index.html/>, last access 25.11.2013.
- Krzywicki, T., 2002. The maximum ice sheet limit of the Vistulian Glaciation in northeastern Poland and neighbouring areas. *Geological Quarterly* 46, 165-188.
- Kümmel, C., 2009. *Ur- und frühgeschichtlicher Grabraub: Archäologische Interpretation und kulturanthropologische Erklärung*. Tübinger Schriften zur Ur- und Frühgeschichtlichen Archäologie 9. Waxmann Verlag, Münster/München.
- Küster, H., 1999. *Geschichte der Landschaft in Mitteleuropa. Von der Eiszeit bis zur Gegenwart*. C.H.Beck Verlag, München.
- Kuszell, T., Chmal, R., Słychan, K., 2007. Early Vistulian climate oscillations in the light of pollen analysis of deposits from Dziadowa Kłoda (Silesian Lowland, Poland). *Geological Quarterly* 51, 319-328.
- Kuttler, W., 2009. *Klimatologie*. Verlag Ferdinand Schöningh, Paderborn.
- KZGW, 2015. Krajowy Zarząd Gospodarki Wodnej, Polish National Department for Water Management. <http://mapa.kzgw.gov.pl/>, last access 10.11.2015.
- Landuydt, C., 1990. Micromorphology of Iron Minerals from Bog Ores of the Belgian Campine Area. *Developments in Soil Science* 19, 289–294.
- Leb, M., 1983. Raseneisenerze in der Oberlausitz – Ein Beitrag zur Geschichte der Raseneisenerzverarbeitung und Geologie der Erzvorkommen. *Sächsische Heimatblätter* 29, 127-132.
- Leser, H., Stäblein, G., 1985. Legend of the geomorphological map 1 : 25 000 (GMK 25) – fifth version in the GMK priority program of the Deutsche Forschungsgemeinschaft. In: *Berliner Geographische Abhandlungen* 39, 61-89.
- Liedtke, H., 1981. *Die Nordischen Vereisungen in Mitteleuropa, Forschungen zur Deutschen Landeskunde*. Band 204. 2nd extended Ed. Zentrallausschuss der Deutschen Landeskunde, Selbstverlag, Trier.
- Lock, G., Harris, T., 2006. Enhancing Predictive Archaeological Modeling: Integrating Location, Landscape, and Culture. In: Mehrer, M., Wescott, K. *GIS and Archaeological Site Location Modeling*.
- Madera, P., 2002. Ślady starożytnego hutnictwa żelaza na Śląsku w ujęciu chronologiczno-przestrzennym. In: Orzechowski, S. *Ślady starożytnego hutnictwa żelaza na Śląsku w ujęciu chronologiczno-przestrzennym*. Śląsk. Świętokrzyskie Stowarzyszenie Dziedzictwa Przemysłowego. Kielce, 61-70.
- Mandel, R. 2000. *Geoarchaeology in the Great Plains*. University of Oklahoma Press, Norman.

- Marks, L., 2012. Timing of the Late Vistulian (Weichselian) glacial phases in Poland. *Quaternary Science Reviews* 44, 81-88.
- Mather, P., Koch, M., 2011. Computer Processing of Remotely-Sensed Images – An Introduction. 4th Ed. Wiley-Blackwell. John Wiley & Sons, Ltd. UK.
- Matthissen, A., 2011. The Iron Age on Zealand – Status and Perspectives. The Royal Society of Northern Antiquaries. Copenhagen.
- Meyer, M., 2008. Mardorf 23, Lkr. Marburg-Biedenkopf. Archäologische Studien zur Besiedlung des deutschen Mittelgebirgsraumes in den Jahrhunderten um Christi Geburt. *Hochschulschrift*. 2 Bände. Berliner Archäologische Forschungen 5.
- Mighall, T., Timberlake, S., Jenkins, D., Grattan, J., 2006. Using bog archives to reconstruct paleopollution and vegetation changes during the late Holocene. In: Martini, P., Martinez Cortizas, A., Chesworth, W. (Eds.). *Peatlands: Evolution and Records of Environmental and Climate Changes. Developments in Earth Surface Processes* 9. Elsevier B.V., Amsterdam, 409-429.
- Mighall, T., Foster, I., Crew, P., Chapman, A., Finn, A., 2009. Using mineral magnetism to characterise ironworking and to detect its evidence in peat bogs. *Journal of Archaeological Science* 36, 130-139.
- Munsell, 2000. Munsell Soil Color Charts. Revised Washable Edition. New York.
- Natural Earth data, 2013. Version 3.1.0. <http://www.naturalearthdata.com/>, last access 15.10.2013.
- North, M., 2007. Europa expandiert 1250 – 1500. *Handbuch der Geschichte Europas* 4. Ulmer Verlag, Stuttgart.
- Olesen, M., 2010. Hvornår starter dansk jernudvinding? Kulstof-14 dateringer af midtjyske jernovne fra ældre jernalder. *Mydtjyske fortællinger*, 83-92.
- Orczewska, A., 2009. Age and Origin of Forests in South-western Poland and their Importance for Ecological Studies in Man-dominated Landscapes. *Landscape Research* 34, 599-617.
- Orzechowski, 2007. The region of iron: the Przeworsk Culture iron producing centre in Barbaricum. In: Crew, P.; Crew, S. (Eds.). *Early Ironworking in Europe II – archaeology, technology and experiment. Abstracts. 2nd International Conference*.
- Orzechowski, S., Suliga, I., 2007. Materials for analysis of post-reduction stages of metallurgical processing at the ancient iron production site at the Góry Świętokrzyskie (Holy Cross Mountains). In: Cauuet, B. (Ed.). *Orfevres et forgerons. L'approche expérimentale en archéologie minière et métallurgique*. Paris.
- Orzechowski, S., 2011. Canal-pit and its role in the bloomery process: the example of the Przeworsk culture furnaces in the Polish territories. In: Hošek, J., Cleere, H., Mihok, L. (Eds.). *The Archaeometallurgy of Iron. Recent Developments in Archaeological and Scientific Research*. Institute of Archaeology of the ASCR. Helvetica and Tempora, Prague.
- Orzechowski, S., 2013. *Region żelaza. Centra hutnicze kultury przeworskiej*. Wydawnictwo Uniwersytetu Jana Kochanowskiego. Kielce.
- Orzechowski, S., Przychodni, A., 2014. Experimental Iron Smelting in the Research on Reconstruction of the Bloomery Process in the Świętokrzyskie (Holy Cross) Mountains, Poland. In: Flores, J., Paardekooper, R. (Eds.). *Experiments Past – Histories of Experimental Archaeology*. Sidestone Press, Leiden.

- Pacina, J., Bruna, V., Cajthaml, J., 2015. Complete 3D Landscape Reconstruction Based on Historical Data Sources. Conference Proceedings 15th International Multidisciplinary Scientific GeoConference SGEM, Book 2, Vol. 1, 547-554.
- Pawlak, W., 1997. Atlas Śląska – Atlas of Lower and Opole Silesia. University of Wrocław and Academy of Sciences, Poland – Department Wrocław. Map sheets 28, 34 and 52.
- Pawłowski, D., Milecka, K., Kittel, P., Woszczyk, M., Spychalski, W., 2014. Palaeoecological record of natural changes and human impact in a small river valley in Central Poland. *Quaternary International*, 1-17.
- Paynter, S., 2006. Regional Variations in Bloomery Smelting Slag of the Iron Age and Romano-British Periods. *Archaeometry* 48, 271-292.
- Pelzer, F., 1991. Polen – Eine geographische Landeskunde. Wissenschaftliche Länderkunden, Band 36. Wissenschaftliche Buchgesellschaft, Darmstadt.
- Piaskowski, J., 1976. Classification of the Structures of Slag Inclusions in Early Objects Made of Bloomery Iron. *Archaeologia Polona* XVII, 139-149.
- Pleiner, R., 1958. Základy slovanského železářského hutnictví v českých zemích. Nakladatelství Československé Akademie Věd. Monumenta Archaeologica 6, Prague.
- Pleiner, R., 2000. Iron in Archaeology – The European Bloomery Smelters. Archeologický ústav AV ČR, Prague.
- Pleiner, R., 2006. Iron in Archaeology – Early European Blacksmiths. Archeologický ústav AV ČR, Prague.
- Pollard, A., 1999. Geoarchaeology: exploration, environments, resources. Geological Society, Special Publication 165, London.
- Puttkammer, T., 2012. Auf den Spuren der Germanen. Begleitband zur Wanderausstellung. Museum der Westlausitz, Kamenz.
- Ramsey, M., Potts, P., Webb, P., Watkins, P., Watson, J., Coles, B., 1995. An objective assessment of analytical method precision: comparison of ICP-AES and XRF for the analysis of silicate rocks. *Chemical Geology* 124, 1-19.
- Rapp, G., Hill, C., 2006. Geoarchaeology – The Earth-Science Approach to Archaeological Interpretation. 2nd Ed. Yale University Press, New Haven and London.
- Ratajczak, T., Rzepa, G., 2011. Lokalne Kopaliny Mineralne A Możliwości Ich Wykorzystania W Ochronie Środowiska. Na Przykładzie Mazurskich Rud Darniowych. *Inżynieria Ekologiczna* 27, 161-169.
- Reimer, P., Bard, E., Bayliss, A., Warren Beck, J., Blackwell, P., Bronk Ramsey, C., Buck, C., Cheng, H., Lawrence Edwards, R., Friedrich, M., Grootes, P., Guilderson, T., Hafliðason, H., Hajdas, I., Hatté, C., Heaton, T., Hoffmann, D., Hogg, A., Hughen, K., Kaiser, K., Kromer, B., Manning, S., Niu, M., Reimer, R., Richards, D., Marian Scott, E., Southon, J.,
- Staff, R., Turney, C., van der Plicht, J., 2013. Intcal13 and Marine13 Radiocarbon Age Calibration Curves 0-50,000 Years Cal BP. *Radiocarbon* 55, 1869-1887.
- Reuter, H., Nelson, A., Jarvis, A., 2007. An evaluation of void filling interpolation methods for SRTM data, *International Journal of Geographic Information Science*". *International Journal of Geographic Information Science* 21, 983-1008.
- Schneider, S., 2014. Geoarchaeological Case Studies in the Bakırçay Valley – Paleogeography and Human-environmental Interactions in the Chora of Pergamon in Western Turkey. Dissertationsschrift. Freie Universität Berlin.

- Schneider, S., Matthaei, A., Schlöffel, M., Meyer, C., Kronwald, M., Pint, A., Schütt, B., 2015. A geoarchaeological case study in the chora of Pergamon, western Turkey, to reconstruct the late Holocene landscape development and settlement history. *Quaternary International* 367, 62-76.
- Schütt, B., 2004. Zum holozänen Klimawandel der zentralen Iberischen Halbinsel. In: Bremer, H., Heine, K., Lauer, W., Hagedorn, H. (Eds.). *Relief Boden Paläoklima* 20. Gebrüder Borntraeger, Berlin, Stuttgart.
- Schwab, R., 2004. Technologie und Herkunft eiserner Werkzeuge und Waffen aus dem spätkeltischen Oppidum von Manching. Dissertation. TU Bergakademie Freiberg.
- Schwab, R., Heger, D., Höppner, B., Pernicka, E., 2006. The Provenance of Iron Artefacts from Manching: A multi-technique approach. *Archaeometry* 48, 433-452.
- Siciński, W., 1996. Wstępne wyniki badań osady ludności kultury przeworskiej w Zadowicach na stan. 1A, woj. kaliskie. *Sprawozdania Archeologiczne* 48, 135-151.
- Sommer, M., 2006. Influence of soil pattern on matter transport in and from terrestrial biogeosystems – A new concept for landscape pedology. *Geoderma* 133, 107-123.
- Sperling, D., 2003. Rohstoffgewinnung und Altbergbau im Förderraum Calau. Beiträge zur Geschichte des Bergbaus in der Niederlausitz 3. Förderverein Kulturlandschaft Niederlausitz e.V. Cottbus.
- Starkel, L., Soja, R., Michczyńska, D., 2006. Past hydrological events reflected in Holocene history of Polish rivers. *Catena* 66, 24-33.
- Stuiver, M., Reimer, P., 1993. Extended C14 Data Base and Revised Calib 3.0 C14 Age Calibration Program. *Radiocarbon* 35, 215-230.
- Thiele, A., 2010. Smelting experiments in the early medieval fajszi-type bloomery and the metallurgy of iron bloom. *Mechanical Engineering* 54/2, 99-104.
- TK25, 1886-1938. Topographic map 1 : 25 000, plane-table sheets 4871 (Bernstadt, 1899), 4872 (Schmograu, 1886), 4971 (Lampersdorf, 1912) and 4972 (Namslau, 1938). Preußische Landesaufnahme.
- TK50, 1992. Topographic map 1 : 50 000, plane-table sheets 453.4 (Olesnica), 454.3 (Namyslow), 463.2 (Olawa) and 464.1 (Wolczyn). Polska Agencja Ekologiczna.
- Todd M., 2004. *The Early Germans*. 2nd Ed. Series *The Peoples of Europe*. Blackwell Publishing.
- Ullrich, B., Kaufmann, G., Kniess, R., Zoellner, H., Meyer, M., Keller, L., 2011. Geophysical Prospection in the Southern Harz Mountains, Germany: Settlement History and Landscape Archaeology Along the Interface of the Latène and Przeworsk Cultures. *Archaeological Prospection* 18, 95-104.
- USGS, 2000. U.S. Geological Survey. SRTM-data set 1 Arc-Second Global. <http://earthexplorer.usgs.gov/>, last access 10.10.2015.
- Verstraeten, G., 2014. Quantification of human-environment interactions in the past. *Anthropocene* 8, 1-5.
- Walanus, A., Nalepka, D., 2005. Wiek Rzeczywisty Granic Chronozon Wyznaczonych Wlatach Radiowęglowych. Roślinne ślady człowieka: Using plants to trace the activities of prehistoric people. *Botanical Guidebooks* 28. Polish Academy of Sciences, Kraków.

- Wallin, P., Österholm, I., Österholm, S., Solsvik, R., 2008. Phosphates and bones: An analysis of the courtyard of marae Manunu, Huahine, Society Islands, French Polynesia. *Terra Australis* 29, 423-434.
- Waters, M., 2000. Alluvial Stratigraphy and Geoarchaeology in the American Southwest. *Geoarchaeology: An International Journal* 15, 537-557.
- Wdowikowski, M., 2014. Wskaźnikowa Ocena Struktury Opadów Atmosferycznych w Zlewni Rzecznej Widawy. *Interdyscyplinarne Zagadnienia w Inżynierii i Ochronie Środowiska* 4, 943-956.
- Werbrouck, I., Antrop, M., Van Eetvelde, V., Stal, C., De Maeyer, P., Bats, M., Bourgeois, J., Court-Picon, M., Crombé, P., De Reu, J., De Smedt, P., Finke, P., Van Meirvenne, M., Verniers, J., Zwertvaegher, A., 2011. Digital Elevation Model generation for historical landscape analysis based on LiDAR data, a case study in Flanders (Belgium). *Expert Systems with Applications* 38, 8178-8185.
- Wiatkowski, M., Rosik-Dukewska, C., Tyminski, T. 2010. Analysis of Water Management of the Michalice Reservoir in Relation to its Functions. *Ecological Chemistry and Engineering* 17, 1505-1516.
- Wielowiejski, J., 1980. Główny szlak bursztynowy w czasach cesarstwa rzymskiego. Zakład Narodowy im. Ossolińskich. Ossolineum. Polska Akademia Nauk. Instytut Historii Kultury Materialnej.
- Wiśniewski, A., Adamiec, G., Badura, J., Bluszcz, A., Kowalska, A., Kufel-Diakowska, B., Mikołajczyk, A., Murczkiewicz, M., Musil, R., Przybylski, B., Skrzypek, G., Stefaniak, K., Zych, J., 2013. Occupation dynamics north of the Carpathians and Sudetes during the Weichselian (MIS5d 3): The Lower Silesia (SW Poland) case study. *Quaternary International* 294, 20-40.
- Wójcicki, K., Marynowski, L., 2012. The organic and mineral matter contents in deposits infilling floodplain basins: Holocene alluviation record from the Kłodnica and Osobłoga river valleys, southern Poland. *Geomorphology* 159-160, 15-29.
- Woyda, S., 1977. Mazowiecki ośrodek hutnictwa starożytnego. *Kwartalnik Historii Kultury Materialnej* 25, 95-104.
- Woyda, S., 2002. Mazowiecki centrum metalurgiczne z młodszego okresu przedrzymskiego i okresu wpływów rzymskich. *Hutnictwo świętokrzyskie oraz inne centra i ośrodki starożytnej metalurgii żelaza na ziemiach polskich*. Kielce, 121-145.
- Woźniak, Z., 1978. A Survey of the Investigations of the Bronze and Iron Age Sites in Poland in 1977. *Sprawozdania Archeologiczne* 30, 263-269.
- Wysota, W., Chruscinska, A., Lankauf, K., Przegietka, K., Oczkowki, H., Szmanda, J., 2000. Chronostratigraphy of the vistulian deposits in the southern part of the Lower Vistula region (north Poland) in the light of TL dating. *Geologos* 5, 123-134.
- Yalçın, Ü., 2000. Zur Technologie der frühen Eisenverhüttung. *Arbeits- und Forschungsberichte zur Sächsischen Bodendenkmalpflege* 42, 307-316.
- Ziegler, P., 1990. Geological Atlas of Western and Central Europe. Shell Verlag. 2nd and completely revised Ed. Geological Society of London. Maatschappij Shell Internationale Petroleum.
- Zygmunt, E., 2009. Alluvial fans as an effect of long-term man–landscape interactions and moist climatic conditions: A case study from the Glubczyce Plateau, SW Poland. *Geomorphology* 108, 58-70.

Appendices

I. Appendix A – Dissertation

Appendix A, Table A.1: Sampling sites of sedimentological samples.

Location	Setting	UTM Coordinates	Drillings	Drilling meter
[Study site]	[Geomorphological situation]	[WGS 1984]	[No]	[summed in m]
Rychnów*	Alluvial fan/Warthe terrace at the Widawa floodplain margin	51°5'32"N, 17°45'18"E	7	31
Lubska*	Weichselian terrace at the Widawa floodplain margin	51°5'15"N, 17°37'25"E	3	11
Młokicie	Holocene terrace at the Widawa floodplain margin	51°5'47"N, 17°35'53"E	3	8
Pielgrzymowice*	Weichselian terrace/tributary at the Widawa floodplain margin	51°6'35"N, 17°34'51"E	3	10

*study sites with an prehistoric iron smelting context according to the AZP (since 1978).

Appendix A, Table A.2: Bulk sediment chemistry of the profiles RYCHNOW12, NAMY02, NAMY03 and NAMY07 comprising MS-, TOC-, TIC-, pH- and EC-values.

Drilling	Depth	MagSus	Water content	TOC (WH-L)*	TOC (LOI550)	TIC (WH)**	TIC (LOI900)	pH	EC
[ID]	[m b.s.]	[SI]	[mass%]	[mass%]	[mass%]	[mass%]	[mass%]		[µS/cm]
RYCHNOW12	36	11.6	22.50	5.46	6.46	0.15	0.17	6.4	281
RYCHNOW12	46	19.1	22.46	4.72	4.86	0.16	0.13	6.3	227
RYCHNOW12	56	18.5	19.30	0.23	3.93	0.14	0.15	6.4	203
RYCHNOW12	66	17.4	18.52	0.11	3.63	0.17	0.14	7.0	196
RYCHNOW12	76	14.2	20.36	2.49	3.78	0.18	0.17	7.0	215
RYCHNOW12	86	8.6	25.56	2.85	4.43	0.15	0.22	6.6	223
RYCHNOW12	93	86.6	34.99	6.97	7.84	0.12	0.22	6.4	197
RYCHNOW12	97	16.5	8.09	0.98	1.33	0.15	0.08	6.6	74
RYCHNOW12	105	7.3	58.51	17.58	18.07	0.32	0.24	5.7	985
RYCHNOW12	115	3.3	70.29	22.30	24.80	0.30	0.36	5.8	843
RYCHNOW12	125	1.9	60.65	15.84	15.53	0.16	0.30	6.0	702
RYCHNOW12	135	3.4	44.59	7.27	8.52	0.19	0.20	6.2	560
RYCHNOW12	145	12.0	31.14	2.70	4.30	0.42	0.16	6.9	449
RYCHNOW12	155	12.6	26.74	1.92	3.39	0.51	0.15	7.0	316
RYCHNOW12	166	9.6	23.15	1.49	2.55	0.68	0.34	7.2	323
RYCHNOW12	175	5.4	22.23	1.23	1.81	1.02	0.82	7.6	362
RYCHNOW12	185	3.5	16.74	0.46	1.28	1.92	1.62	7.9	222
RYCHNOW12	196	8.5	25.08	1.25	2.64	1.38	1.07	7.5	234
RYCHNOW12	205	14.9	57.26	11.09	10.36	0.51	0.32	6.5	412
RYCHNOW12	210	32.1	35.07	2.09	2.37	0.27	0.12	6.9	591
RYCHNOW12	220	69.9	29.42	3.00	0.00	0.98	2.20	6.9	713
RYCHNOW12	230	91.6	70.50	12.65	8.21	0.85	0.43	6.7	587
RYCHNOW12	240	8.5	55.88	13.12	9.64	0.38	0.26	6.5	461
RYCHNOW12	250	9.2	41.42	4.93	6.15	0.33	0.30	7.3	355
RYCHNOW12	260	10.7	39.45	3.54	5.65	0.44	0.35	7.0	180
RYCHNOW12	270	14.5	41.52	3.02	5.29	0.27	0.25	6.9	380
RYCHNOW12	280	10.8	35.83	2.16	3.89	0.37	0.39	7.1	322
RYCHNOW12	290	8.6	25.61	1.09	2.33	1.30	0.91	7.5	184
RYCHNOW12	295	6.6	18.72	0.71	1.56	1.57	1.24	7.9	151
RYCHNOW12	306	22.9	6.83	0.20	0.63	0.30	0.05	8.4	200
RYCHNOW12	315	31.8	14.05	0.00	0.75	0.67	0.04	7.8	192
RYCHNOW12	325	37.2	66.04	18.11	14.27	1.59	0.97	7.2	306
RYCHNOW12	328	24.1	33.48	2.94	3.86	1.48	0.58	7.4	421
RYCHNOW12	335	20.4	53.49	5.46	4.35	0.40	0.11	6.9	464
RYCHNOW12	345	17.5	67.46	20.12	18.54	0.38	0.38	6.4	469
RYCHNOW12	355	12.2	54.95	9.27	9.32	1.13	0.19	6.7	474
RYCHNOW12	360	19.8	45.12	5.61	6.14	1.05	0.51	7.1	470
RYCHNOW12	370	12.1	57.41	10.49	8.60	1.91	1.07	7.0	271
RYCHNOW12	382	21.2	36.63	3.25	4.02	1.22	1.04	7.6	404
RYCHNOW12	390	11.9	11.31	0.34	1.09	0.46	0.03	8.2	266
RYCHNOW12	405	9.2	13.96	0.00	0.40	0.52	0.02	8.2	153
RYCHNOW12	415	10.4	12.94	0.00	0.44	0.35	0.01	8.4	129
RYCHNOW12	425	10.1	11.88	0.00	0.48	0.39	0.00	8.3	151
RYCHNOW12	435	13.0	8.69	0.00	0.34	0.40	0.02	8.4	130
RYCHNOW12	447	14.1	26.93	0.88	1.21	0.35	0.00	7.9	193
RYCHNOW12	455	6.0	14.68	0.15	0.34	0.17	0.00	8.0	174
RYCHNOW12	465	11.8	23.25	1.14	1.80	0.43	0.09	7.7	151
RYCHNOW12	475	5.8	11.18	0.00	0.29	0.21	0.00	8.1	121
RYCHNOW12	490	30.7	16.64	0.01	0.92	0.56	0.06	7.8	378
RYCHNOW12	496	9.9	12.65	0.11	0.67	0.18	0.01	6.6	452
RYCHNOW12	505	9.6	10.46	0.00	0.48	0.47	0.07	8.7	144
RYCHNOW12	515	9.2	9.21	0.11	0.52	0.15	0.01	8.6	161
RYCHNOW12	525	9.8	8.96	0.00	0.37	0.24	0.00	8.5	124
RYCHNOW12	535	9.5	12.99	0.00	0.48	0.25	0.02	8.5	186
RYCHNOW12	545	47.0	3.39	0.00	0.30	0.70	0.18	8.8	167
RYCHNOW12	560	80.1	10.86	0.00	1.22	1.79	0.59	7.7	192
RYCHNOW12	570	21.7	9.55	0.06	1.20	0.80	0.56	7.6	217
RYCHNOW12	580	22.6	8.22	0.31	1.15	0.54	0.57	7.6	259
RYCHNOW12	590	22.9	7.93	0.28	1.11	0.56	0.63	7.5	255
NAMY02	49	17.2	23.88	3.43	4.32	0.00	0.27	5.6	141
NAMY02	59	11.8	19.54	2.57	3.45	0.02	0.23	5.3	116
NAMY02	69	12.1	21.02	2.33	3.23	0.03	0.23	5.5	116
NAMY02	79	17.8	5.63	0.72	0.78	0.03	0.11	5.9	102
NAMY02	89	17.9	18.76	1.23	2.32	0.01	0.31	5.8	89
NAMY02	96		25.05	3.04	4.28	0.02	0.33	6.0	78
NAMY02	99		24.32	2.21	2.92	0.02	0.27	6.2	95

Drilling	Depth	MagSus	Water content	TOC (WH-L)*	TOC (LOI550)	TIC (WH)**	TIC (LOI900)	pH	EC
[ID]	[m b.s.]	[SI]	[mass%]	[mass%]	[mass%]	[mass%]	[mass%]		[μS/cm]
NAMY02	107	13.6	19.50	1.79	2.20	0.02	0.19	6.3	43
NAMY02	117	12.5	17.82	1.16	2.44	0.03	0.18	6.4	42
NAMY02	127	14.2	19.09	1.12	1.65	0.03	0.17	6.4	41
NAMY02	137	12.0	21.83	0.97	1.48	0.46	0.48	7.1	50
NAMY02	147	12.6	22.32	0.81	1.52	1.07	1.10	7.3	68
NAMY02	155	16.1	18.66	0.56	1.18	0.87	0.87	7.3	58
NAMY02	165	43.4	29.40	0.78	4.32	3.54	2.27	7.1	70
NAMY02	175	28.6	25.54	0.67	2.87	3.40	2.67	7.2	76
NAMY02	185	26.5	26.43	0.76	3.04	4.08	3.34	7.2	70
NAMY02	195	30.6	27.49	0.56	3.49	4.95	3.76	7.3	75
NAMY02	199		25.88	0.46	1.45	3.92	3.64	7.4	112
NAMY02	212	19.2	25.13	0.86	2.16	1.62	1.29	7.3	70
NAMY02	222	19.9	27.69	0.63	2.68	3.97	3.28	7.4	61
NAMY02	232	9.7	29.30	0.46	1.52	5.36	4.95	7.5	55
NAMY02	242	8.8	25.78	0.72	1.20	4.86	4.95	7.6	100
NAMY02	249	7.6	32.86	1.15	1.93	4.30	4.20	7.6	98
NAMY02	259	4.2	37.76	0.81	1.41	9.69	9.55	7.8	82
NAMY02	269	6.3	42.33	7.01	7.87	2.77	2.58	7.3	98
NAMY02	279	5.0	45.08	9.05	9.64	1.45	1.31	6.8	109
NAMY02	289	10.1	43.15	7.46	7.70	0.28	0.09	6.4	123
NAMY02	299		49.47	8.10	8.39	0.38	0.25	5.6	421
NAMY02	307	26.6	50.28	8.90	9.76	2.10	1.51	6.9	430
NAMY02	317	44.8	48.51	7.97	8.47	0.71	0.28	6.9	440
NAMY02	327	32.3	69.30	22.49	23.88	0.71	0.53	6.7	449
NAMY02	337	34.3	71.93	26.13	28.00	0.77	0.48	6.6	459
NAMY02	347	24.4	35.52	4.87	4.98	0.26	0.16	6.4	468
NAMY02	357	6.2	11.54	0.47	0.14	0.02	0.07	7.0	47
NAMY02	367	7.6	16.01	0.63	0.55	0.00	0.09	6.5	48
NAMY02	373	7.6	17.09	0.66	0.69	0.02	0.19	6.3	51
NAMY02	383	7.8	22.14	1.51	1.57	0.03	0.12	6.0	53
NAMY02	393	8.9	18.69	1.09	1.02	0.03	0.12	5.7	120
NAMY02	399		24.56	1.76	1.80	0.03	0.26	4.1	670
NAMY02	405	1.5	11.79	0.49	0.30	0.09	0.02	7.3	105
NAMY02	415	1.5	11.49	0.43	0.19	0.05	0.00	7.5	71
NAMY02	425	5.5	21.04	1.27	1.30	0.02	0.24	5.9	108
NAMY02	435	2.5	13.35	0.50	0.25	0.02	0.05	6.2	55
NAMY02	445	2.9	14.06	0.42	0.09	0.04	0.07	6.1	100
NAMY02	455	0.7	12.00	0.42	0.19	0.02	0.02	6.5	57
NAMY02	465		16.75	0.55	0.34	0.05	0.02	7.0	54
NAMY03	5	23.8	13.97	1.82	2.72	0.25	0.08	5.2	115
NAMY03	15	17.6	12.44		2.32		0.16	4.3	132
NAMY03	25	13.2	13.00		2.02		0.13	4.7	110
NAMY03	35	7.3	13.32		1.75		0.10	5.1	92
NAMY03	45	8.1	8.56		1.16		0.07	5.4	63
NAMY03	55	5.8	10.32	0.84	1.70	0.31	0.07	5.5	72
NAMY03	59	7.4	8.59		1.26		0.07	5.7	51
NAMY03	69	12.5	10.61		1.01		0.05	5.7	59
NAMY03	78	15.5	10.28		0.81		0.19	5.7	42
NAMY03	87	12.2	10.85		0.81		0.04	5.7	41
NAMY03	96	75.6	8.40		0.59		0.04	5.8	25
NAMY03	99	22.5	13.03		0.57		0.04	5.9	40
NAMY03	105	20.5	12.12		0.52		0.04	5.8	41
NAMY03	115	9.5	13.35		0.60		0.05	5.8	34
NAMY03	125	9.7	13.54		0.48		0.04	5.9	42
NAMY03	135	15.0	18.80		0.81		0.06	5.2	51
NAMY03	145	48.1	43.84	1.48	7.06	0.14	0.25	5.3	100
NAMY03	155	54.8	37.54		7.12		0.32	6.1	130
NAMY03	165	55.4	38.49	0.92	7.04	5.51	4.19	6.3	105
NAMY03	175	44.3	38.53	1.13	7.77	0.55	0.45	7.1	95
NAMY03	185	49.5	35.75		6.93		4.98	7.3	85
NAMY03	192	20.6	35.88	1.17	5.55	6.51	5.87	7.4	69
NAMY03	201	24.2	35.15	0.69	5.65	6.94	5.96	7.6	85
NAMY03	210	8.2	39.85	1.51	2.38	10.69	10.29	7.6	86
NAMY03	216	9.6	17.13		0.76		0.27	7.6	88
NAMY03	226	11.3	13.03		0.39		0.09	7.7	58
NAMY03	237	26.6	12.08	0.00	0.42	0.71	0.08	7.7	54
NAMY03	243	15.1	17.54		0.88		0.15	7.6	58
NAMY03	248	51.8	23.40		1.05		0.16	7.6	125
NAMY03	257	4.1	17.77		0.23		0.04	8.0	61
NAMY03	266	2.2	16.26		0.13		0.03	8.1	47
NAMY03	275	1.4	17.06		0.13		0.04	8.2	43
NAMY03	285	0.7	16.36		0.14		0.03	7.8	49

Drilling	Depth	MagSus	Water content	TOC (WH-L)*	TOC (LOI550)	TIC (WH)**	TIC (LOI900)	pH	EC
[ID]	[m b.s.]	[SI]	[mass%]	[mass%]	[mass%]	[mass%]	[mass%]		[μS/cm]
NAMY03	291	0.4	14.45		0.17		0.03	8.0	47
NAMY03	310	2.6	15.48		0.13		0.03	8.0	40
NAMY03	320	2.3	15.68		0.16		0.03	7.6	34
NAMY03	330	4.2	15.59		0.15		0.04	7.5	29
NAMY03	340	5.2	15.66		0.46		0.08	7.6	38
NAMY03	348	14.2	14.58		1.28		0.21	7.6	53
NAMY03	352	17.9	24.25		3.05		0.43	7.3	50
NAMY03	356	20.6	23.32	0.27	2.94	0.38	0.61	7.5	79
NAMY03	363	27.9	22.72	0.00	6.28	2.78	0.50	7.4	63
NAMY03	374	14.6	13.67		1.27		0.21	7.5	67
NAMY03	385	20.4	14.17		1.28		0.33	7.5	75
NAMY03	395	13.5	13.43		1.30		0.38	7.6	83
NAMY03	399	11.7	14.11	0.43	1.45	0.43	0.41	7.4	75
NAMY03	405		16.60		0.37		0.08	7.6	52
NAMY03	415	13.6	15.59		0.30		0.07	7.7	54
NAMY03	425	11.3	16.55		0.56		0.11	7.8	62
NAMY03	435	14.3	16.62		0.72		0.15	7.8	52
NAMY03	445	13.9	16.84		0.86		0.17	7.9	53
NAMY03	455	15.9	16.84		0.87		0.18	7.9	73
NAMY03	465	14.2	14.18	0.75	1.43	0.15	0.38	7.7	82
NAMY03	475	29.7	13.55		1.24		0.48	7.7	125
NAMY03	485	19.2	13.07		1.37		0.49	7.7	66
NAMY03	495	10.1	16.33		1.37		0.44	7.5	60
NAMY03	499	11.2	17.34	0.26	1.76	0.02	0.62	7.3	60
NAMY07	8	21.6	29.77	2.93	4.25	0.24	0.13	5.6	151
NAMY07	15	14.9	25.28		3.29		0.11	5.3	274
NAMY07	21	14.8	21.02		2.44		0.11	4.8	238
NAMY07	30	16.6	18.68		2.01		0.10	5.1	206
NAMY07	39	16.0	14.53		1.82		0.10	5.1	176
NAMY07	49	11.3	22.69	1.12	2.56	0.44	0.14	5.1	163
NAMY07	59	6.2	13.48		0.73		0.05	5.2	76
NAMY07	63	12.7	15.17	0.78	1.49	0.01	0.07	5.2	105
NAMY07	66	7.4	14.73		0.82		0.05	5.2	93
NAMY07	73	7.6	19.46	0.86	1.74	0.30	0.11	5.2	139
NAMY07	83	11.7	11.62		0.62		0.05	5.1	69
NAMY07	93	14.7	13.25		0.62		0.05	5.4	57
NAMY07	99		14.18		0.67		0.05	5.3	69
NAMY07	105		13.15		0.75		0.05	5.3	43
NAMY07	115	14.0	14.98		0.86		0.07	5.3	49
NAMY07	125	28.6	16.98	0.61	1.09	0.07	0.10	5.0	96
NAMY07	134	19.6	17.72	0.00	1.01	0.68	0.09	4.7	109
NAMY07	144	33.0	13.44		0.68		0.07	4.7	74
NAMY07	154	8.4	13.58		0.39		0.05	4.6	62
NAMY07	164	4.8	14.14		0.41		0.06	4.6	54
NAMY07	174	6.2	12.34		0.47		0.08	4.7	46
NAMY07	184	2.7	10.29		0.21		0.02	5.2	30
NAMY07	194		11.25	0.40	0.23	0.08	0.04	5.6	35
NAMY07	198		12.22		0.29		0.06	5.7	40
NAMY07	203	10.9	13.99		0.96		0.15	6.1	46
NAMY07	213	10.1	15.73		1.05		0.16	6.1	82
NAMY07	223	7.3	10.95		0.40		0.06	6.3	50
NAMY07	233	5.3	12.17		0.27		0.06	6.3	46
NAMY07	243	9.7	11.31	0.22	0.37	0.21	0.08	6.2	59
NAMY07	253	12.3	11.56		0.13		0.03	6.3	54
NAMY07	263	453.3	10.86		0.23		0.05	6.3	55
NAMY07	270	230.7	13.51		0.27		0.05	6.4	75
NAMY07	338	16.4	12.84		0.87		0.26	7.0	122
NAMY07	348	18.6	12.58		0.98		0.35	7.1	121
NAMY07	358	14.9	11.68		0.85		0.28	7.1	110
NAMY07	364	12.0	17.25		1.82		0.28	7.1	112
NAMY07	375	14.1	10.76	0.35	0.91	0.16	0.31	7.4	109
NAMY07	380	13.2	3.26	0.01	0.36	0.30	0.09	7.3	114
NAMY07	384	13.9	16.46	0.00	1.70	0.50	0.28	7.1	120
NAMY07	394	17.9	10.65		1.27		0.31	7.0	178
NAMY07	399	18.9	12.32		1.22		0.34	7.2	217

Appendix A, Table A.3: Complete record of radiocarbon dates.

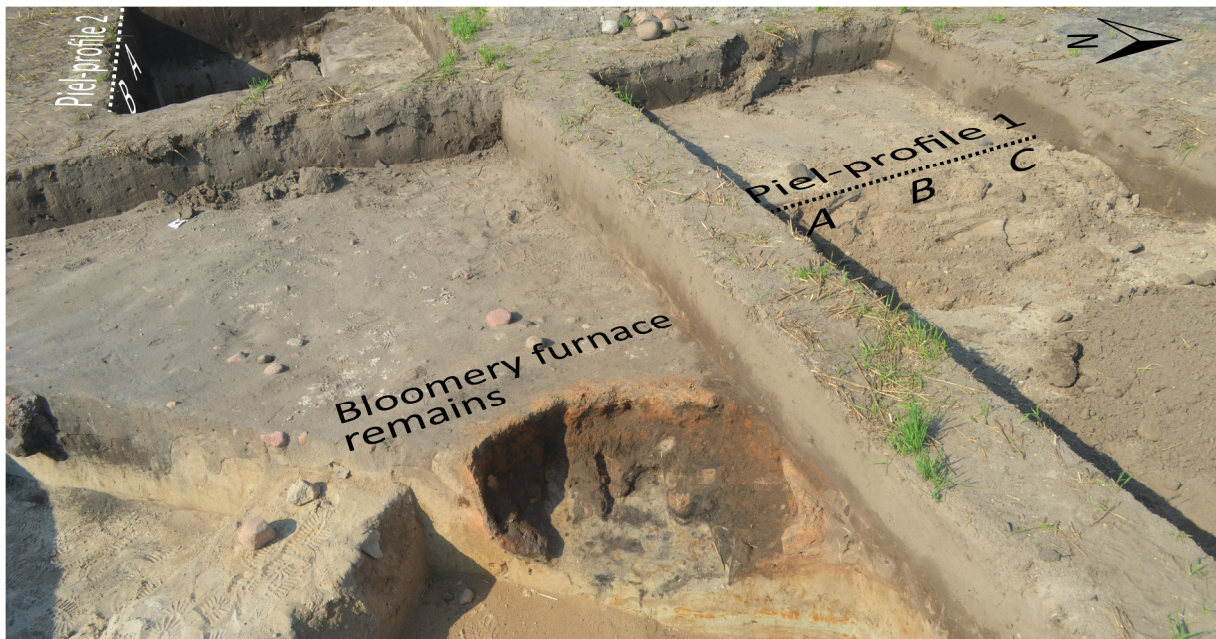
ID	Sample ID	Drilling ID	Location [nearby village]	Type [carbon reservoir]	Sampling depth [cm b.s.]	Uncalibrated age** [a BP]	Calibrated age [cal. ka BP, 2σ]
1	Poz-58500	NAMY01	Rychnów*	Charcoal fragment	72	109.01 ± 0.31	0.14 ± 0.11****
2	Poz-58501	NAMY01	Rychnów*	Charcoal fragment	127	2,050 ± 30	2.11 ± 0.09****
3	Poz-59785	NAMY02	Rychnów*	Charcoal fragment	138	2,450 ± 70	2.54 ± 0.18****
4	Poz-59786	NAMY02	Rychnów*	Macroplant remains	303	7,330 ± 40	8.15 ± 0.13****
5	Poz-59787	NAMY02	Rychnów*	Macroplant remains	437	8,820 ± 50	9.92 ± 0.24****
6	Poz-59788	NAMY03	Rychnów*	Charcoal fragment	114	2,960 ± 70	3.14 ± 0.21****
7	Poz-59712	NAMY03	Rychnów*	Macroplant remains	204	1,625 ± 30	1.50 ± 0.09****
8	Poz-71465	NAMY03	Rychnów*	Charcoal fragment	215	1,615 ± 30	1.49 ± 0.08****
9	Poz-59713	NAMY03	Rychnów*	Charcoal fragment	482	> 51,000	> 51.0
10	Poz-58502	NAMY04	Młokicie	Charcoal fragment	46	900 ± 30	0.82 ± 0.09****
12	Poz-58504	NAMY04	Młokicie	Charcoal fragment	96	1,185 ± 30	1.11 ± 0.11****
11	Poz-58505	NAMY04	Młokicie	Charcoal fragment	194	2,960 ± 60	3.14 ± 0.19****
13	Poz-59714	NAMY06	Młokicie	Macroplant remains	129	2,245 ± 30	2.55 ± 0.09****
14	Poz-59715	NAMY06	Młokicie	Charcoal fragment	268	37,200 ± 700	41.49 ± 1.15****
15	Poz-58590	PiF5-1	Pielgrzymowice*	Charcoal fragment	66	2,280 ± 40	2.26 ± 0.10***
16	Poz-58506	PiF5-1	Pielgrzymowice*	Charcoal fragment	83	2,110 ± 30	2.14 ± 0.14***
17	Poz-58507	PiF5-2	Pielgrzymowice*	Charcoal fragment	60	2,180 ± 50	2.19 ± 0.14***
18	Poz-58508	PiF5-2	Pielgrzymowice*	Charcoal fragment	69	3,270 ± 35	3.49 ± 0.09***
19	Poz-58509	PiF5-2	Pielgrzymowice*	Charcoal fragment	97	2,090 ± 30	2.07 ± 0.08***
20	Poz-68342	LUBSKA09	Lubska*	Bulk sample	238	38,000 ± 900	42.10 ± 1.46****
21	Poz-68343	LUBSKA09	Lubska*	Macroplant remains	454	39,000 ± 1,000	43.06 ± 1.55****
22	Poz-71621	RYCHNOW12	Rychnów*	Bulk sample	105	565 ± 30	0.58 ± 0.06****
23	Poz-71464	RYCHNOW12	Rychnów*	Macroplant remains	371	9,420 ± 80	10.75 ± 0.33****
24	Poz-68346	RYCHNOW13	Rychnów*	Charcoal fragment	149	2,005 ± 30	1.96 ± 0.08****
25	Poz-68344	PIELW14	Pielgrzymowice*	Macroplant remains	218	9,770 ± 60	11.09 ± 0.21****
26	Poz-68345	PIELW14	Pielgrzymowice*	Macroplant remains	269	15,480 ± 180	18.74 ± 0.18****

*study sites with prehistoric iron smelting context according to AZP (since 1978) **measured at Poznan Radiocarbon Laboratory, Poland.

***calibration with Calib Rev 7.0.1 with the calibration curve IntCal13 after Reimer et al. (2013).

****calibration with OxCal 4.2 (Bronk Ramsey and Lee, 2013) with the calibration curve IntCal13 after Reimer et al. (2013).

IV. Appendix D – Case study IV



Appendix D, Fig. A.1: Piel-profiles 1A/B/C and 2A/B in the immediate vicinity of a bloomery furnace in trench 3 (Photo: Thelemann, 2014).



Appendix D, Fig. A.2: Piel-profiles 3A/B and 4A/B in trench 5 (Photo: Thelemann, 2014).

Appendix D, Table A.1: Laboratory results of the profiles in the exaction sections.

Sample ID	Piel-profile	Position Vert./hor.	Grain size < 2 mm	Grain size > 2 mm	Water content	pH value	est.CaCO ₃ [10%HCl]	LOI550	est. TOC (LOI550)	est. TC (LOI)	Phosphate spot test	Ca* 317.93	Cd* 228.80	Cr* 357.87	Cu* 224.70	Fe* 238.20	K* 766.49	Mg* 279.08	Mn* 257.61	Na* 589.59	Ni* 231.60	P* 213.62	Pb* 220.35	Sr* 460.73	Zn* 213.86
No	Profile ID	[in cm]	[mass%]	[mass%]	[mass%]	[°]	[mass%]	[mass%]	[mass%]	[mass%]	[in classes]	[mg/g]	[µg/g]	[µg/g]	[µg/g]	[mg/g]	[mg/g]	[mg/g]	[mg/g]	[mg/g]	[µg/g]	[mg/g]	[µg/g]	[µg/g]	[µg/g]
1	1A	31	96.62	3.38	0.21	6.4	0.0	1.24	0.72	0.77	1.0	1.08	0.09	6	19	4.16	0.45	0.42	0.31	0.18	7	0.77	3	4.51	30
2	1A	36	97.28	2.72	0.28	6.2	0.0	0.95	0.55	0.59	2.0	0.93	0.12	6	16	3.48	0.40	0.38	0.22	0.13	6	0.72	3	4.01	23
3	1A	41	96.94	3.06	0.29	6.1	0.0	0.95	0.55	0.58	2.0	0.87	0.02	6	12	2.75	0.45	0.34	0.19	0.23	6	0.57	2	4.42	17
4	1A	46	94.27	5.73	1.72	6.0	0.0	4.22	2.46	2.69	2.0	0.88	0.03	5	13	2.59	0.43	0.32	0.14	0.16	7	0.49	2	4.50	15
5	1A	51	97.84	2.16	0.10	6.0	0.0	0.53	0.31	0.32	1.5	0.70	0.03	5	10	2.01	0.40	0.28	0.13	0.26	6	0.42	2	3.80	13
6	1A	56	98.76	1.24	0.07	5.8	0.0	0.37	0.22	0.23	2.0	0.41	0.00	5	7	1.47	0.36	0.23	0.03	0.27	5	0.26	1	2.94	9
7	1A	61	98.87	1.13	0.16	5.7	0.0	0.29	0.17	0.19	1.5	0.44	0.00	4	6	1.50	0.34	0.24	0.02	0.25	5	0.27	1	3.01	8
8	1A	66	98.93	1.07	0.09	5.6	0.0	0.25	0.15	0.18	2.0	0.36	0.00	4	8	1.49	0.33	0.20	0.05	0.19	5	0.25	1	2.92	8
9	1B	31	96.50	3.50	4.35	5.8	0.0	1.40	0.81	0.87	1.0	1.21	0.10	8	13	4.50	0.59	0.50	0.30	0.18	7	0.92	4	5.20	27
10	1B	36	96.54	3.46	0.23	5.7	0.0	1.30	0.76	0.79	1.0	0.99	0.04	7	13	5.02	0.53	0.43	0.25	0.16	7	0.78	3	4.90	20
11	1B	41	94.42	5.58	0.21	5.6	0.0	1.25	0.73	0.77	1.5	0.94	0.04	6	11	4.21	0.52	0.44	0.23	0.24	6	0.78	3	4.98	18
12	1B	51	88.88	11.12	0.27	5.6	0.0	2.39	1.39	1.45	2.0	1.97	0.02	9	13	5.81	0.89	0.73	0.22	0.46	7	1.36	2	10.09	19
13	1B	56	94.74	5.26	0.18	5.6	0.0	1.28	0.74	0.78	1.0	1.17	0.04	7	8	2.92	0.71	0.48	0.11	0.22	6	0.89	2	6.56	16
14	1B	61	98.36	1.64	0.06	5.6	0.0	0.44	0.25	0.29	2.5	0.49	0.00	6	8	2.14	0.40	0.27	0.04	0.19	5	0.41	2	3.72	9
15	1B	66	99.17	0.83	0.08	5.7	0.0	0.58	0.34	0.37	2.0	0.68	0.01	6	8	2.54	0.46	0.39	0.05	0.29	6	0.77	2	4.55	11
16	1C	31	97.22	2.78	0.22	5.5	0.0	1.26	0.73	0.79	1.0	0.78	0.15	7	11	3.60	0.52	0.42	0.25	0.22	7	0.80	4	4.24	21
17	1C	36	97.85	2.15	0.09	5.3	0.0	0.61	0.35	0.38	1.0	0.44	0.03	5	7	2.09	0.46	0.27	0.08	0.25	6	0.45	2	2.89	12
18	1C	41	97.83	2.17	0.05	5.2	0.0	0.51	0.29	0.32	1.0	0.39	0.00	5	5	1.59	0.29	0.23	0.03	0.18	8	0.27	1	2.66	12
19	1C	46	98.78	1.22	0.06	5.2	0.0	0.41	0.24	0.27	1.0	0.42	0.00	5	7	1.61	0.33	0.23	0.04	0.19	5	0.23	1	2.81	10
20	1C	51	99.20	0.80	0.23	5.2	0.0	0.35	0.21	0.24	1.0	0.36	0.00	4	4	1.67	0.35	0.23	0.03	0.20	5	0.29	2	2.71	10
21	1C	56	99.34	0.66	0.47	5.3	0.0	0.39	0.23	0.26	1.0	0.42	0.00	4	5	1.82	0.33	0.25	0.04	0.15	5	0.29	1	2.77	8
22	1C	61	99.28	0.72	0.05	5.4	0.0	0.45	0.26	0.30	1.0	0.43	0.00	5	4	2.40	0.37	0.26	0.07	0.11	5	0.44	2	3.02	8
23	1C	66	98.98	1.02	0.05	5.4	0.0	0.36	0.21	0.25	1.0	0.46	0.01	4	4	1.76	0.26	0.22	0.07	0.66	4	0.42	2	2.90	6
24	2A	5	97.16	2.84	0.19	5.4	0.0	2.52	1.46	1.56	1.0	1.24	0.22	9	13	5.62	0.84	0.68	0.34	0.19	6	1.45	17	5.82	36
25	2A	10	95.69	4.31	0.22	5.4	0.0	2.60	1.51	1.61	1.0	1.25	0.19	9	10	6.03	0.77	0.66	0.34	0.30	7	1.34	15	5.56	33
26	2A	15	96.07	3.93	0.28	5.8	0.0	2.90	1.69	1.80	1.5	1.56	0.21	10	10	5.94	0.80	0.72	0.37	0.15	6	1.45	15	6.27	35
27	2A	20	95.06	4.94	0.28	5.9	0.0	2.51	1.46	1.82	1.0	1.46	0.21	9	10	5.56	0.78	0.73	0.35	0.15	7	1.34	14	6.56	34
28	2A	25	96.24	3.76	0.23	5.8	0.0	1.94	1.13	1.25	2.0	1.25	0.13	8	10	6.13	0.59	0.58	0.38	0.14	6	1.23	9	5.59	32
29	2A	32	94.93	5.07	0.34	5.8	0.0	1.99	1.16	1.26	1.5	1.24	0.10	8	10	6.50	0.62	0.53	0.43	0.28	8	1.35	7	6.08	29
30	2A	37	92.03	7.97	0.39	5.6	0.0	1.94	1.13	1.22	1.5	1.52	0.09	8	10	8.12	0.69	0.57	0.46	0.15	7	1.71	5	8.14	29
31	2A	45	87.49	12.51	0.32	5.6	0.0	1.91	1.11	1.21	1.5	1.46	0.11	9	10	7.64	0.70	0.61	0.50	0.25	8	1.61	4	8.55	29
32	2A	51	95.56	4.44	0.22	5.8	0.0	1.52	0.88	0.97	1.0	1.20	0.10	6	11	4.91	0.63	0.45	0.34	0.13	5	1.22	4	6.60	21
33	2A	57	94.69	5.31	0.23	5.9	0.0	1.32	0.77	0.86	1.0	1.28	0.07	6	10	4.03	0.45	0.37	0.33	0.21	6	1.17	3	6.58	18
34	2A	65	94.94	5.06	2.63	6.0	0.0	1.23	0.71	0.78	2.0	1.27	0.03	5	9	4.39	0.49	0.33	0.24	0.16	5	1.29	3	6.46	15
35	2A	70	94.62	5.38	0.15	5.9	0.0	1.19	0.69	0.75	2.0	1.53	0.09	5	13	4.65	0.44	0.29	0.61	0.13	10	1.70	3	8.08	17
36	2A	75	95.27	4.73	0.15	6.0	0.0	1.32	0.77	0.82	2.0	1.39	0.03	4	11	3.35	0.37	0.23	0.14	0.14	5	1.35	2	7.62	13
37	2A	81	96.98	3.02	0.09	6.0	0.0	1.11	0.64	0.70	1.0	0.87	0.00	4	8	1.56	0.43	0.20	0.05	0.17	7	0.48	2	5.28	9
38	2A	88	95.92	4.08	0.02	6.0	0.0	0.22	0.13	0.14	1.5	0.53	0.00	4	3	1.35	0.27	0.19	0.06	0.18	4	0.18	3	3.37	5
39	2B	5	90.60	9.40	0.26	5.8	0.0	2.60	1.51	1.71	1.0	1.17	0.17	9	9	5.28	0.78	0.64	0.34	0.10	7	1.29	14	5.22	32
40	2B	10	96.85	3.15	0.27	5.7	0.0	2.54	1.48	1.59	1.0	1.35	0.16	10	10	5.63	0.78	0.67	0.37	0.16	6	1.38	15	8.26	32
41	2B	15	95.95	4.05	0.20	5.4	0.0	2.28	1.33	1.44	1.0	1.21	0.17	9	10	6.02	0.79	0.62	0.36	0.13	7	1.28	14	5.75	36
42	2B	20	97.01	2.99	0.37	5.5	0.0	2.31	1.34	1.48	1.0	1.22	0.15	9	9	5.61	0.82	0.61	0.34	0.18	7	1.31	16	6.99	33
43	2B	25	99.11	0.89	0.19	5.7	0.0	2.28	1.33	1.48	1.0	1.65	0.21	10	9	6.69	0.70	0.81	0.35	0.12	6	1.49	15	5.93	39
44	2B	32	95.45	4.55	0.16	5.8	0.0	1.68	0.98	1.06	1.0	1.20	0.06	7	10	4.55	0.58	0.51	0.32	0.17	6	0.95	6	4.99	24
45	2B	39	95.26	4.74	0.11	5.8	0.0	0.65	0.38	0.40	1.0	0.58	0.01	4	8	1.87	0.28	0.22	0.10	0.19	5	0.38	2	3.06	9
46	2B	46	97.11	2.89	0.09	5.8	0.0	0.89	0.52	0.55	1.0	0.71	0.00	5	6	2.14	0.44	0.29	0.10	0.19	5	0.44	2	3.78	11
47	2B	55	97.93	2.07	0.05	5.8	0.0	0.32	0.19	0.19	1.0	0.35	0.00	3	3	0.95	0.25	0.14	0.03	0.13	5	0.14	1	2.31	5
48	2B	60	98.44	1.56	0.03	5.8	0.0	0.24	0.14	0.15	1.0	0.35	0.00	3	3	0.84	0.30	0.14	0.02	0.16	4	0.11	1	2.62	5

Sample ID	Piel-profile	Position	Grain size	Grain size	Water	pH	est.CaCO ₃	LOI550	est. TOC	est. TC	Phosphate	Ca*	Cd*	Cr*	Cu*	Fe*	K*	Mg*	Mn*	Na*	Ni*	P*	Pb*	Sr*	Zn*
No	Profile ID	Vert./hor. [in cm]	> 2 mm [mass%]	< 2 mm [mass%]	content [mass%]	value [°]	[10%HCl] [mass%]	[mass%]	(LOI550) [mass%]	(LOI) [mass%]	spot test [in classes]	317.93 [mg/g]	228.80 [µg/g]	357.87 [µg/g]	224.70 [µg/g]	238.20 [mg/g]	766.49 [mg/g]	279.08 [mg/g]	257.61 [mg/g]	589.59 [mg/g]	231.60 [µg/g]	213.62 [mg/g]	220.35 [µg/g]	460.73 [µg/g]	213.86 [µg/g]
49	2B	65	98.38	1.62	0.01	5.7	0.0	0.21	0.12	0.13	1.0	0.30	0.00	3	3	0.75	0.25	0.12	0.02	0.21	4	0.15	1	2.29	4
50	2B	70	98.19	1.81	0.02	5.7	0.0	0.21	0.12	0.13	1.0	0.34	0.00	3	3	0.70	0.28	0.13	0.02	0.20	4	0.10	1	2.54	4
51	2B	75	97.92	2.08	0.00	5.6	0.0	0.25	0.15	0.15	1.0	0.38	0.00	4	3	1.11	0.39	0.20	0.03	0.19	5	0.13	1	3.14	5
52	2B	80	95.29	4.71	0.02	5.6	0.0	0.23	0.13	0.14	1.0	0.35	0.00	4	2	0.79	0.25	0.15	0.02	0.34	9	0.29	1	2.59	5
53	2B	85	100.00	0.00	0.07	5.6	0.0	0.40	0.23	0.25	1.0	0.61	0.01	5	3	1.57	0.41	0.29	0.06	0.19	5	0.31	2	3.47	8
54	2B	90	100.00	0.00	0.15	5.6	0.0	0.71	0.41	0.47	1.5	0.77	0.00	8	4	3.63	0.70	0.58	0.09	0.21	7	0.69	3	5.55	15
55	3A	0	96.09	3.91	0.29	6.0	0.0	1.99	1.16	1.26	1.0	1.25	0.09	9	9	5.37	0.76	0.71	0.29	0.11	8	1.11	9	5.87	24
56	3A	10	95.97	4.03	0.27	5.9	0.0	1.91	1.11	1.19	2.0	1.37	0.06	10	8	5.96	0.89	0.76	0.28	0.19	7	1.10	8	6.31	26
57	3A	20	94.85	5.15	0.31	6.0	0.0	2.00	1.16	1.25	1.5	1.55	0.09	11	8	6.52	0.96	0.88	0.31	0.20	9	1.19	8	7.26	27
58	3A	30	95.36	4.64	0.25	5.9	0.0	1.81	1.05	1.14	1.5	1.41	0.06	10	8	6.24	0.85	0.79	0.26	0.20	8	1.11	8	9.20	26
59	3A	40	96.49	3.51	0.43	6.0	0.0	2.25	1.31	1.43	2.0	1.74	0.05	15	9	9.03	1.39	1.23	0.24	0.17	11	1.37	11	9.46	29
60	3A	50	97.07	2.93	0.46	6.0	0.0	2.16	1.26	1.41	2.0	1.81	0.05	19	9	10.55	1.47	1.52	0.18	0.27	11	1.27	7	9.58	29
61	3A	60	99.57	0.43	0.66	6.0	0.0	2.50	1.45	1.64	2.0	2.19	0.05	22	9	13.34	1.77	1.79	0.18	0.16	12	1.42	9	10.92	33
62	3A	70	97.18	2.82	0.60	5.8	0.0	2.48	1.44	1.60	1.5	1.91	0.07	20	9	12.46	1.67	1.63	0.18	0.26	12	1.41	9	10.03	35
63	3A	80	98.76	1.24	0.58	5.8	0.0	2.46	1.43	1.59	2.0	1.84	0.08	21	8	11.19	1.64	1.55	0.16	0.14	11	1.39	9	9.80	32
64	3A	90	94.32	5.68	0.46	5.8	0.0	2.24	1.30	1.44	2.0	1.77	0.13	16	9	9.25	1.45	1.23	0.25	0.20	10	1.40	13	9.21	30
65	3A/3B	100	100.00	0.00	0.55	5.7	0.0	2.50	1.45	1.64	2.0	1.95	0.08	22	10	12.16	1.72	1.71	0.17	0.17	12	1.31	10	10.58	29
66	3B	90	94.50	5.50	0.26	6.1	0.0	1.99	1.15	1.25	2.0	1.44	0.08	11	9	6.52	0.93	0.87	0.29	0.24	8	1.17	7	7.28	26
67	3B	80	94.16	5.84	0.28	6.1	0.0	2.14	1.25	1.35	2.0	1.37	0.08	10	9	6.29	0.88	0.81	0.34	0.15	8	1.12	7	6.88	24
68	3B	70	95.76	4.24	0.33	6.1	0.0	2.24	1.30	1.42	2.0	1.48	0.09	11	9	6.62	0.90	0.84	0.30	0.27	8	1.29	8	7.39	26
69	3B	60	82.07	17.93	0.45	6.0	0.0	2.61	1.52	1.67	2.5	2.03	0.08	17	9	9.57	1.39	1.37	0.25	0.24	11	2.84	9	14.84	32
70	3B	50	95.03	4.97	0.39	6.0	0.0	2.26	1.31	1.46	1.5	1.72	0.05	15	9	9.62	1.14	1.36	0.18	0.17	10	1.24	8	8.44	26
71	3B	40	97.18	2.82	0.38	6.0	0.0	2.10	1.22	1.35	2.0	1.62	0.05	15	8	8.54	1.34	1.23	0.22	0.20	11	1.33	8	9.25	25
72	3B	30	97.28	2.72	0.35	5.9	0.0	1.97	1.15	1.27	1.5	1.44	0.20	13	8	7.49	1.06	1.06	0.23	0.16	8	1.18	7	7.87	28
73	3B	20	95.56	4.44	0.30	6.0	0.0	2.01	1.17	1.28	1.5	1.42	0.10	13	8	7.19	1.09	1.02	0.25	0.21	9	1.14	9	7.72	25
74	3B	10	95.73	4.27	0.26	6.0	0.0	1.72	1.00	1.10	1.5	1.23	0.04	10	7	6.08	0.84	0.80	0.27	0.16	7	1.03	9	6.28	22
75	3B	0	95.30	4.70	0.24	6.0	0.0	1.71	0.99	1.09	2.0	1.26	0.09	10	7	6.34	0.92	0.80	0.30	0.15	9	1.05	9	6.63	24
76	4A	0	93.98	6.02	0.16	6.1	0.0	1.25	0.73	0.78	2.0	0.93	0.03	8	5	4.13	0.70	0.65	0.13	0.14	6	0.74	5	5.43	16
77	4A	10	95.35	4.65	0.17	6.1	0.0	1.57	0.91	1.03	2.0	1.06	0.08	9	5	4.93	0.76	0.71	0.19	0.23	7	0.97	7	5.84	20
78	4A	20	93.90	6.10	0.22	6.0	0.0	1.70	0.99	1.12	2.0	1.37	0.05	12	6	6.35	1.11	1.06	0.14	0.17	9	1.19	5	8.03	23
79	4A	30	91.72	8.28	0.26	6.0	0.0	1.99	1.16	1.27	2.0	1.54	0.06	12	7	7.07	1.17	1.01	0.20	0.23	8	1.49	7	8.64	25
80	4A	40	95.37	4.63	0.44	5.9	0.0	2.07	1.20	1.37	1.5	1.65	0.13	19	7	9.61	1.33	1.35	0.15	0.14	10	1.32	11	8.49	26
81	4A	50	82.48	17.52	0.60	5.9	0.0	2.51	1.46	1.66	2.0	2.20	0.09	21	8	9.69	1.77	1.32	0.15	0.18	10	8.47	7	21.46	36
82	4A	60	96.53	3.47	0.22	6.0	0.0	1.64	0.96	1.04	3.0	1.48	0.10	9	9	5.62	0.86	0.73	0.33	0.14	8	1.21	10	7.04	26
83	4A	70	95.53	4.47	0.29	6.0	0.0	2.27	1.32	1.43	2.0	1.46	0.09	9	9	5.25	0.80	0.67	0.35	0.13	7	1.16	9	7.04	24
84	4A	80	95.08	4.92	0.27	6.0	0.0	2.18	1.27	1.38	2.0	1.75	0.09	9	10	5.62	0.80	0.72	0.39	0.15	8	1.17	6	7.32	26
85	4A	90	94.69	5.31	0.24	6.0	0.0	1.82	1.06	1.14	2.0	1.43	0.06	8	9	5.62	0.70	0.67	0.33	0.13	6	1.10	7	6.19	23
86	4A/4B	100	81.71	18.29	0.49	5.8	0.0	2.10	1.22	1.42	2.0	1.76	0.03	19	8	11.64	1.51	1.51	0.15	0.18	11	1.22	8	9.07	26
87	4B	90	87.00	13.00	0.35	5.8	0.0	1.84	1.07	1.24	2.0	1.46	0.05	15	8	9.16	1.30	1.24	0.18	0.16	9	0.98	7	8.10	24
88	4B	80	84.87	15.13	0.29	5.8	0.0	1.83	1.06	1.23	2.0	1.38	0.06	14	7	8.52	1.19	1.16	0.17	0.15	9	0.96	8	7.70	24
89	4B	70	88.58	11.42	0.51	5.9	0.0	6.38	3.71	3.87	2.0	1.47	0.05	15	8	8.75	1.21	1.19	0.22	0.17	9	1.05	7	8.07	24
90	4B	60	77.89	22.11	0.42	6.0	0.0	2.40	1.40	1.56	3.0	2.26	0.09	16	9	9.60	1.55	1.26	0.27	0.20	11	3.47	8	14.69	34
91	4B	50	92.82	7.18	0.34	5.9	0.0	2.44	1.42	1.54	2.0	1.82	0.08	10	12	6.07	0.85	0.86	0.35	0.14	8	1.30	7	8.92	27
92	4B	40	94.22	5.78	0.31	5.9	0.0	2.44	1.42	1.54	2.0	1.98	0.08	10	11	6.93	1.21	1.00	0.39	0.12	10	1.34	6	8.23	30
93	4B	30	95.89	4.11	0.24	6.0	0.0	2.05	1.19	1.31	2.0	1.45	0.09	9	8	5.33	0.78	0.71	0.34	0.13	6	1.09	15	6.72	26
94	4B	20	95.38	4.62	0.25	6.0	0.0	1.92	1.12	1.22	2.0	1.22	0.11	10	7	5.26	0.74	0.63	0.30	0.13	7	1.16	11	5.81	27
95	4B	10	92.70	7.30	0.25	6.0	0.0	2.05	1.19	1.29	2.0	1.47	0.07	8	10	5.05	0.73	0.65	0.38	0.26	7	1.20	7	6.73	25
96	4B	0	95.89	4.11	0.16	6.0	0.0	2.01	1.17	1.26	1.5	1.33	0.12	9	8	5.54	0.74	0.66	0.33	0.20	10	1.18	10	6.28	27

*Measured with ICP-OES in the geoscientific laboratory of the Freie Universität Berlin.

Curriculum Vitae

Der Lebenslauf ist in der Online-Version aus Gründen des Datenschutzes nicht enthalten.

Eidesstattliche Erklärung

Hiermit erkläre ich, Michael Thelemann, dass ich die Dissertation *Human and Environment Interactions in the Environs of Prehistorical Iron Smelting Places in Silesia, Poland – Landscape Archaeological and Geoarchaeological Investigations in the Context of Early Iron Smelting* selbständig angefertigt und keine anderen als die von mir angegebenen Quellen und Hilfsmittel verwendet habe.

Weiterhin erkläre ich, dass ich diese Dissertation in dieser oder anderer Form in keinem früheren Promotionsverfahren, sondern erstmalig am Fachbereich Geowissenschaften der Freien Universität Berlin eingereicht habe.

Berlin, den 15. April 2016