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„Extending the archaeometry toolbox through multidisciplinary data interpretations“

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Motivation

> *„Je mehr Faktoren und Zusammenhänge eine Analyse im Interesse der Erklärung eines Systemmerkmals wie Wachstum oder eines Ereignisses wie einer Wirtschaftskrise einbezieht, umso deutlicher stößt sie an zwischen Disziplinen gezogene Wissensgrenzen, die es übrigens nicht nur zwischen Rechts-, Wirtschafts- und Sozialwissenschaften, sondern auch zwischen diesen und verschiedenen Natur- und Technikwissenschaften gibt. Die Tatsache solcher Wissensgrenzen verweist eindringlich auf die unvermeidliche Beschränktheit disziplinärer Erkenntnismöglichkeiten."* (Mayntz 2009), p.34

Interdisciplinary research or interdisciplinarity has been a widely used term since the second half of the 20th century (Kröber 1983). It became a kind of trademark and an expression for high quality research comparable to "excellence" (Laitko 2011). It is also an important motor for the development of each scientific discipline, as each of these can benefit from interactions with others. Other terms describing different types of interaction of disciplines are multi, poly-, trans- or pandisciplinary. Interdisciplinary research also attempts to adapt methodological and theoretical framework of each invloved discipline to a specific research question or topic (or phenomenon). In contrary in multidisciplinary research, methods of different disciplines are applied for a specific research question, without any major changes in each discipline. Arguing the detailed definitions for each type is not as important as the knowledge about the positive feedback of this disciplinary interaction for all involved disciplines (Kröber 1983).

Archaeology and archaeological sciences are a perfect example, where different disciplines must interact, and clearly can benefit from this interaction. This interaction is even more challenging, as most disciplines from natural sciences and humanities can be included.[1]

Personally I was fascinated and surprised by the emerging contradictions of these two basic approaches of sciences as soon as I found myself studying physics and archaeology. In the first archaeometry course during the second semester of my studies I was astonished by the different ways natural scientists and scientists of humanities and their students viewed given phenomena differently, which also resulted in the speaking of different scientific languages. This hasn´t changed significantly since that time and was the impetus for my enrolling in courses in philosophy in addition

[1] In avoiding a theoretical archaeological discussion regarding whether archaeology is related to the humanities or the natural sciences, I rather refer to the fact, that different methods from both scientific branches are applied within archaeological research.

to my other coursework. After finishing my master degree in physics my focus of research has been on archaeological sciences, which led to a lot of interdisciplinary discussions. I always found it very useful and necessary to declare my practical and theoretical academic background to illustrate my "vocabulary". This is also the main impetus for writing a very personal motivation for this thesis. Although my *curriculum vitae* is necessarily enclosed within this work, I would like to integrate a few additional aspects of my academic development to illustrate my personal paradigm.

Within my studies of archaeology I also focused on experimental archaeology. This archaeological subdiscipline attempts to investigate archaeological materials, artifacts and contexts regarding their use and creation through an experimental setup. I was fascinated by the technical skills, which must be elaborated, and by the application of a method, which has been successfully applied in physics over centuries – the experiment. In physics, the axioms for an experiment are clearly defined, as an experiment must fulfill the demands of reproducibility, quantification and analysis (Pietschmann 1996). It is a probing question as to whether and how these axioms can be valid for an experiment in archaeology. Experimental archaeology is a perfect example where neither natural sciences nor humanities would be able to find a satisfying answer, without adapting theoretical concepts from each other (see also an early work Kucera 2004).

After finishing my master degree in physics, I began working at the Vienna Institute of Archaeological Sciences (VIAS) in operating an atmospheric secondary electron microscope with additional energy dispersive x-ray spectrometry. During a short stay at the Römisch-Germanisches Zentralmuseum in Mainz/ Germany (RGZM) I was also allowed to work with a µXRF to establish a calibration curve for ancient bronze, based on recent standards for this specific spectrometer. It was the first time I was confronted with the absence of respective standards, as ancient bronze – like most other archaeological samples - is signified by a huge variation of material composition, which makes nearly every archaeological artifact unique. This uniqueness turns out to be a major criterion for characterizing archaeological material in general. Sometimes this uniqueness and varying composition makes a quantification of results difficult. It is often more fruitful to qualitatively compare respective results. For interpreting results in this way much expert knowledge--not only from one discipline--is crucial, which necessitates an interdisciplinary dialogue. During this time I personally benefitted from collaborations with different disciplines of humanities and natural sciences. These collaborations provided the chance to analyze a problem from different perspectives.

The more perspectives that can be included, the more respective patterns or common relations or laws can be argued. Detecting a pattern is a very subjective process, either done by a human being or well-trained computer algorithms. Within this process it must be determined whether something is important or not. This decision always seems to be subjective, which implies that the observer somehow is determining the observation. This can be compared to fundamental interpretations of quantum mechanics, only an observation determines a discrete state or result. A main challenge is to gain reproducibility and comparability of results based on subjective decisions and observations and their basic relation to objectivity and subjectivity respectively.

The decision for elaborating skills in archaeological excavation and documentation techniques was also motivated by the demand for understanding under which conditions archaeological samples are generated. Knowledge about specimen treatment prior to sample processing and analysis is crucial for reproducible results. In 2011 I became technical director of excavations carried out at the sites of Ochsenberg and Hornsburg, both in Lower Austria. Within a multidisciplinary team, we tried to apply and introduce various different analytical methods on site. Some of these results will be presented and discussed within this thesis.

Since 2010 I have been a researcher at the Ludwig Boltzmann Institute for archaeological prospection and virtual archaeology (LBI ArchPro) based in Vienna/ Austria. The research team consists of scientists with multiple disciplinary backgrounds. One of the major case studies of the institute is situated in the area of Kreuttal/ Lower Austria. Respective results for elaborating data acquisition techniques and the integrated interpretation of different datasets will be presented in this thesis.

I am aware that all single results seen from the point of view of a specific discipline may not be highly remarkable, nevertheless the challenge of archaeological research is to derive results through the interaction of these disciplines. As mentioned earlier, every discipline benefits from an interdisciplinary approach (Kröber 1983). In this respect archaeological sciences always have the potential to evolve the theoretical and practical framework of contributing disciplines. Whereas the first step towards a collaboration of different disciplines is communication, a basic knowledge of the respective scientific vocabulary is crucial. With this short section I first wanted to illustrate the impetus which motivated me for the presented research. Secondly, I wish to present how I labored to implement these different scientific vocabularies through explicit inquiry into a general perception of interdisciplinary and multidisciplinary advantages but also its pitfalls and limits.

Introduction

It is often said that every archaeological site – and even every artifact - is unique (Harris 1989). Thus it must be the challenge of archaeological research to reveal patterns of similar rules and processes for describing and understanding observed phenomena. As with all sciences, results must be reproducible, which is guaranteed through the well-defined use of methodology. This multiple application of different types of methods results in a huge variety of data, which must be compared and interpreted in an integrated approach. The creation and accurate definition of methodological rules for this comparison and integrated analysis are a central issue for the theoretical framework of archaeological sciences. Some of these aspects regarding limitations and validity of specific methods, the comparability of different results and the entanglement of applied method and observed phenomenon will be discussed within this thesis. Different methods can be applied for various archaeological research questions, whereas results achieved strongly depend on the specific archaeological context. For example archaeological evidence might be detected through the application of selected methods of archaeological prospection, whereas others of these methods fail due to environmental settings (Löcker et al. 2015).

All archaeological data have the common factor of being linked to a geographical location and a specific time interval (Drap et al. 2017). Archaeological research therefore deals mainly with the spatio-temporal analysis of relations of archaeological entities and information corresponding to them. Geographical Information Systems (GIS) have been proven to fulfill the expectations in dealing with the archiving, organization and analysis of big archaeological datasets (Neubauer 2004). Respectively, GIS software provides the visualization of different aspects of gathered data, spatio-temporal analysis and the basis for an integrated interpretation of the data. For a valid integrated interpretation of results based on a multidisciplinary approach, the data must be analyzed within a four dimensional context provided by GIS functionality including the time component. Every applied method must be clearly defined regarding its limits and basic abilities. This is mainly dependent on the context in which an archaeological structure or artifact is found and its basic material properties. Both aspects must be carefully examined and properly tested within different methodological approaches. It is a common archaeological statement that only something known can be found. Through the well-defined application of different methods and the constant observation of a given research question from multiple perspectives of various disciplines aspects thus far unknown can be revealed. For this purpose an interdisciplinary communication of the involved disciplines is necessary based on collaborative accord, scientific language and definitions.

Archaeology versus archaeological sciences

Historical overview

Archaeology is relatively young compared to other major scientific disciplines. Although people have been always more or less interested in the material remains of past human societies, archaeology started to clearly evolve as a methodologically defined discipline only in the 18th century. In the 19th century different branches such as classical archaeology and prehistoric archaeology evolved. From this time on until the first half of the 20th century archaeology focused mostly on the analysis of artifacts and architectural remains in the context of the humanities. All archaeological disciplines have a geographically dependent relation to social anthropology. Although social anthropology and archaeology are historically motivated by the same scientific interests, namely the description and investigation of human societies, their hierarchical relation varies a lot within respective academic traditions (compare also Bahn 2014; Eggert 2012; Veit 1990). Whereas anthropology is assigned to natural sciences, the disciplinary position of archaeology is still widely discussed. It can be also argued that archaeology bridges the gap between natural sciences and humanities.

Today archaeology has seen a paradigm change towards the steadily growing application of methods and techniques derived from natural sciences (compare also (Andrews and Doonan 2003). These can be summarized under the terms archaeological sciences or archaeometry, respectively. In general methods and techniques can be divided into ones applied for the investigation of objects and others for the detection and analysis of archaeological evidence in general. The first can be referred to as being part of analytical archaeometry unifying different disciplines from physics, chemistry, life sciences, material sciences and engineering. The second group consists of methods traditionally identified as archaeological prospection including remote sensing, field walking and geophysical prospection. All archaeological sciences share the common thread of requiring close collaboration with each other and to archaeology itself.

Especially non-invasive and minor-invasive archaeological prospection and material analysis has become more and more important over the past decades. Keeping in mind that most archaeological heritage is currently under threat, the application of these techniques is crucial for the analysis and preservation of archaeological landscapes and cultural heritage. Only recently the "European Convention on the Protection of the Archaeological Heritage (Valetta Treaty)" initiated by the Council of Europe[2] was ratified by most European states. It is the aim of the signing members "to protect the archaeological heritage as a source of the European collective memory (Valetta treaty, Article 1.1) (*European Convention on the Protection of the Archaeological Heritage* 1992)." It is stressed that

[2] The Council of Europe shall not be confused with organizations and governmental structures of the European Union. It was founded in 1949 and has so far 47 member states.

non-invasive investigation techniques must be preferred and precede unavoidable archaeological excavations. Excavations provide only a spatially narrow view and, in most cases, destroy archaeological evidence irretrievably. They might yet be justified, if the archaeological evidence is under threat or scientifically relevant results based on previously well-defined research questions can be expected (*European Convention on the Protection of the Archaeological Heritage* 1992).

For the display and further analysis of the results a relatively new branch of archaeological sciences has evolved, namely virtual or cyber archaeology (VAR). The application of so many different methods necessarily leads to a big amount of data. These data and the methods they originate from show, to some extent, huge differences regarding the background given by the theory of science. A main challenge is to guarantee the comparability of these different types of data to provide the basis of an integrated interpretation of the respective results. VAR provides techniques and methods not only for reconstructing archaeological structures and architecture; it is also a useful tool to fuse data, simulate processes and visualize data in different ways for better comparability (compare also (Barceló et al. 2000; Forte and Kurillo 2010).

The challenge of multidisciplinary archaeological research

In contrary to natural sciences, archaeological research questions can rarely be limited to a manageable amount of parameters. Due to its scientific aim, namely to investigate the spatio-temporal development of human societies, strict limitations are difficult to be realized. Whereas for example in physics, interfering parameters are investigated and avoided in order to analyze different aspects of an observed phenomenon in a reproducible manner (Pietschmann 1996), this can hardly be achieved in archaeological research in general. Therefore an archaeological context must be described as an open system. An open system, as described by Luhmann for social sciences, exchanges, in contrast to an isolated system, information, material and also people with other systems (Luhmann 1995). To characterize an archaeological system, it also includes as yet unknown parameters, which influence the system as well. An archaeological system is therefore a double open system, as regards the social and physical environment. The social environment is part of the main focus of archaeological research. It is first of all manifested through anthropogenic material remains. The physical environment is determined by observable and interacting physical and chemical properties (compare also (Shahack-Gross 2017).

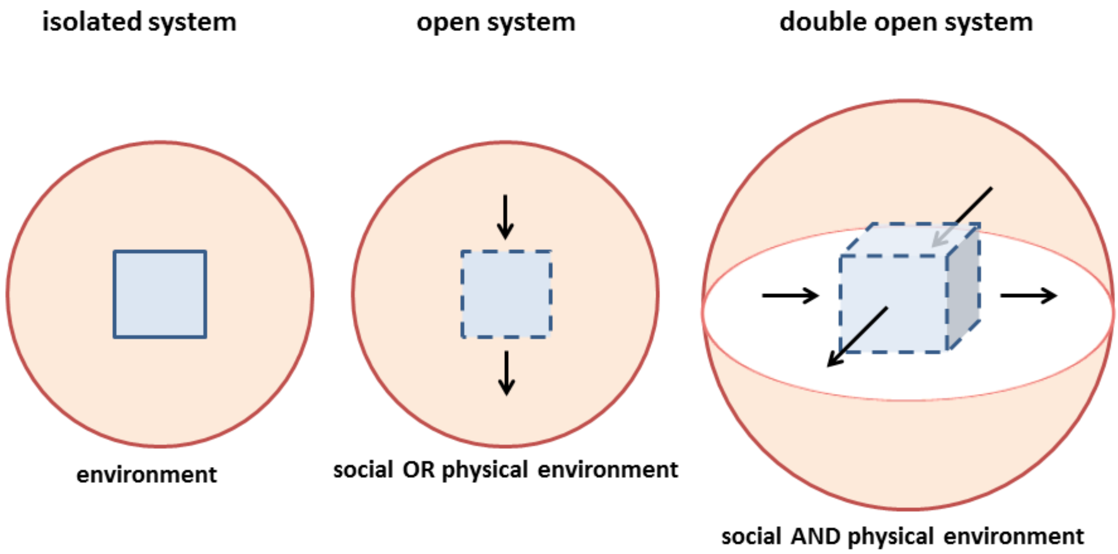

Figure 1: According to system theory a system can be isolated or open regarding its environment (Luhmann 1995). Archaeological systems depend on social and physical environment and could be described as double open (© M.Kucera).

It is the challenge of archaeological research to define and describe this system, i.e. the specific archaeological evidence, regarding its influences, characteristics, purpose, functionality and origin. For this investigation the selection of applied methods is crucial, as this is also often linked to personal skills and preferences[3]. The composition of the set of applied methods implements a preselection of results and already forces a shift of possible scientific interpretation of the observed phenomena. For this reason a clearly defined approach starting with the formulation of a specific research question and the selection of suitable methods according to given standards is necessary. Each applied method can only examine aspects of a phenomenon according to its limits and within a certain error range. Based on these results - each provided by well-defined methods and methodological approach – an integrated interpretation of the phenomenon can be achieved. For the integrated interpretation standardized concepts and strategies must be provided to achieve a reproducibility and traceability of the results.

When methods of natural sciences were first introduced for the examination of archaeological research questions, archaeologists were fond of the possible quantification of observed phenomena. However, quantification in a strictly scientific sense is hardly achieved within archaeological contexts. This is due firstly to the uniqueness of every archaeological phenomenon including artefacts and

[3] This opens a wide discussion regarding objectivity in science. For detailed exemplary reading the work of Pietschmann, Latour, Daston and Gallison could be recommended (Pietschmann (1990), Latour (1999), Daston and Galison (2009))

sites. Secondly archaeological interpretation and analysis of a phenomenon is not only based on its material aspects. Archaeology also seeks to derive knowledge about social structures and behavior from the analysis of material remains. This aspect needs to be included in a complete description. This is the moment when data meets argument. Whereas humanities rely mostly on arguments derived from logical guessing and are therefore closer to the philosophy of rationalism, natural sciences evolve their results from empiric observations resulting in data. When analyzing results in an integrated way, one must always be aware of this polarity of archaeology and archaeological sciences.

Archaeological sciences, their application and the integrated interpretation of their results are a challenge for both natural sciences and archaeology and its context within the humanities. Collaborative research in sciences is necessary to answer archaeological questions satisfactorily. Natural scientists can profit in respect to methodological development from the application of methods within an unexpected context and in correlation with other disciplines. Therefore archaeological sciences provide not only important input for archaeological research but also for the development and improvement of existing methodology.

Aim of this thesis

Within this thesis, novel approaches of archaeological prospection, namely motorized magnetic prospection together with examples of the application of methods of material analysis, will be presented. Remote sensing techniques have always provided the potential to cover large areas for the detection of archaeological evidence, and recently the development of motorized geophysical prospection have opened up the realm for geophysical surveys (Neubauer et al. 2014; Gaffney et al. 2012; Trinks et al. 2012). Among these, motorized magnetic prospection devices and their application will be described in detail. The physical interpretation of the results gained relies mainly on the understanding of the geophysical properties of the observed phenomena (normally referred to as anomalies or features in geophysical prospection). Thus a detailed analysis regarding geological and pedological aspects and the influence of environmental settings (e.g. humidity) is needed (Schneidhofer et al. 2016). For the investigation of the material composition and physical properties of observed anomalies several methods of archaeological sciences can be applied. As an example, the application of pXRF for the on-site measurement of the composition of excavated archaeological structures will be presented. It is very important for the understanding of archaeological samples that not only the composition, but also the structure is examined. For this purpose the complementary analysis provided by secondary electron microscopy (SEM) combined with an energy dispersive x-ray detection unit (EDX) is very useful. For the analysis of archaeological samples atmospheric SEM is of great advantage as it allows investigating the specimen without further treatment regarding the optimization of conductivity. The insight into the inner structure of archaeological samples and artifacts reveal the heterogeneity of these. Therefore it is crucial to have both a qualitative depiction of the surface structure provided by SEM imaginary and the respective quantitative analysis of the material composition.

As every archaeological phenomenon and the information related to it can be identified by a geographical position, geographical information systems (GIS) are widely applied for the archiving, managing, display and analysis of archaeological data (Neubauer 2004). For the analysis of the temporal component such a system must be extended by a concept for controlling and displaying time. Systems like these are referred to as GIS-based archaeological information systems (G-AIS) (Carver 2005)with a prefix 4D if they include a temporal component (Drap et al. 2017). It is the basis for the integrated interpretation and spatio-temporal analysis of archaeological data and information.

In order to summarize the main objectives influencing the reproducible integrated interpretation of a multidisciplinary archaeological dataset, the following aspects must be taken in account: (1) the principle heterogeneity and uniqueness of archaeological samples and phenomena, (2) the interaction of the selected applied methods and the phenomenon under investigation influencing the expected results and (3) the necessity of applying only well-defined methods according to standardized procedures. All methods must be implemented and their respective results interpreted according to their principle limits and validation. Once this is done results can be used for the integrated interpretation. A possible environment for this integrated approach can be a 4D G-AIS, which provides also the necessary metadata to weight results within different contextual settings. In applying multiple methods it is crucial that the origin of the final results and hypothesis is traceable.

It is the aim of this thesis to suggest and elaborate the basic principles for dealing with multidisciplinary datasets and their integrated interpretation. For this purpose selected methods of archaeological sciences will be described (pXRF, SEM, geophysical prospection). Nevertheless, the most challenging question to be answered regards the limits and pitfalls of multidisciplinary or interdisciplinary collaborations.

Description of the state-of-the-art

The variety of different methods applied for archaeological sciences is rapidly increasing (Canti and Huisman 2015). New methods are constantly being added to the methodological repertoire from nearly all available scientific but also artistic and technical disciplines. In this respect archaeology seems to develop towards a multidisciplinary subject with the need for truly interdisciplinary theoretical and methodological framework (Lidén and Eriksson 2013). Most projects and grants could therefore be seen within this context. Nowadays it is quite common that different disciplines are engaged within a single archaeological project; it is actually rather exceptional that projects are limited to a purely archaeological approach. In this sense multidisciplinary projects and approaches are state-of-the-art in archaeology and of course archaeological sciences. Although this approach is widely accepted, descriptions and definitions of standardized rules for interdisciplinary work are just now evolving and are a constant challenge of everyday scientific work (Izdebski et al. 2016; Garrow and Shove 2007). Most scientists engaged in archaeological research agree on the necessity of multidisciplinary collaborations, even though a common sense regarding the applicability of specific methods has not yet been achieved. Single methods are often criticized regarding the validity of their results within a concrete context. This happens especially when the results of different methods contradict one another. Whereas each method seems to be well-defined, valid and elaborated rules in which context which method should be preferred are rare. This is also due to the enormous variety of archaeological scenarios of different phenomena. For this reason the aforementioned rules must be elaborated and tested for nearly every archaeological setting. Therefore recent investigations have also begun to deal with these aspects of the principle structure of interdisciplinary or rather multidisciplinary work based on strict rules. The aim is to provide stringent guidelines for the selection of specific methods, their application and the separate interpretation of the results of each method within an integrated setting.

Archaeological Prospection

The different methods summarized under archaeological prospection are currently widely accepted as providing excellent data for the detection of archaeological evidence and spatial analysis of whole archaeological landscapes. The main categories are remote sensing and geophysical prospection. The latter will be in the focus of this thesis.

Remote Sensing

Remote sensing can be divided into two general branches of techniques and methods. One is analyzing the physical properties of the surfaces (e.g. radiation and humidity) using different sensors, the other is documenting the surface of the terrain. The later has seen a significant increase since the introduction of aerial laser scanning (ALS) combined with the application of various mathematical filters to virtually remove the vegetation cover within the topographical data. With these techniques it has also become possible to investigate the topography of forested areas (Doneus et al. 2008). Recently ALS was also applied for bathymetry in the detection of submerged archaeological structures in shallow coastal water (Doneus et al. 2013). Within the last 5 years also 3D data capturing based on image based modeling (IBM) has also become a standard method for the rapid and cost effective recording of surfaces and archaeological structures (Reu et al. 2013). The method has been successfully applied both for aerial (Fernández-Hernandez et al. 2015) and ground-based recording. Another technique for ground based 3D recording is terrestrial laser scanning (TLS), which was introduced at the start of the millennium and applied for archaeological purposes soon after (Doneus and Neubauer 2006; Neubauer 2007). Whereas IBM and TLS are often seen as opponents, their application is mostly complementary. For the effective recording of archaeological heritage a combination of both techniques is preferred. Aerial archaeology is within archaeological prospection the method that has been successfully applied for the longest time. Through the application of GNSS (global navigation satellite system), inertial measurement units (IMU) and automated processes for the geographical location and the rectification of imaginary aerial archaeology has recently seen further improvement (Doneus et al. 2016; Verhoeven et al. 2012).

Geophysical prospection

Since the second half of the 20th century geophysical prospection has seen rising application in archaeology (Neubauer 2001; Scollar et al. 1990). The most common methods successfully applied for archaeological purposes, include:

- magnetic prospection
- ground penetrating radar (GPR)
- electro resistivity
- electromagnetic induction (EMI)
- seismic prospection
- measurement of susceptibility

All these methods analyze and display physical properties of the near surface, when being used in a configuration optimized for archaeological settings. Traditionally sensors were carried across fields or mounted to hand carts. For positioning, grids consisting of lines were placed on the ground and georeferenced with a totalstation. A lot of effort was put into the post processing of the data in developing respective software (Hinterleitner et al. 2009). Results were promising from the beginning although the general acceptance for this methodology was sometimes rather poor. Another aspect was, that the investigation of larger areas was very time consuming. This changed with the introduction of motorized systems. First attempts started very early (Sørensen 1996; Panissod et al. 1998), but were also limited by the existing acquisition software. The latest developments regarding the design and testing of suitable carts to mount sensors, of vehicles to tow these systems, of optimized acquisition software and of accurate GNSS based solutions for navigation and positioning enabled the prospection of large areas on the scale of landscapes (Trinks et al. 2010b; Gaffney et al. 2012). Within a comparably short period of a few years, mostly motorized GPR, magnetic prospection and EMI devices were used more often for geophysical prospection. Systems are still more or less custom-made regarding the towing vehicles, carts, implementation of positioning systems, navigation and data acquisition software and standardized survey routines. Although the systems are theoretically capable of surveying large areas per day, only the strict application of daily routines including logistics, maintenance, data management and data processing allow maximizing reproducible scientific output. Another challenge is the investigation of the influencing environmental parameters such as geological and pedological background, humidity and soil composition (Schneidhofer et al. 2016). Recently projects have been launched to analyze the dependencies between these parameters and the applied geophysical prospection technique. Seasonal environmental changes can influence the quality of results significantly. It is crucial for the perception of the reliability of these methods within the scientific archaeological community have exact knowledge about these limiting factors in order to provide the best results.

All these developments lead to the wide acceptance of archaeological prospection techniques for effectively providing basic data for the detection and investigation of archaeological evidence. Even more, the importance of archaeological prospection for the non-invasive documentation and analysis of archaeological heritage is indicated through the Valetta Treaty. The effectiveness of the applied methodology is also illustrated by the increase of awareness from public and governmental organizations. As infrastructural development often comes into conflict with the preservation of archaeological and cultural heritage, preceding archaeological prospection became more and more a standard throughout the last years (Martinho and Dionísio 2014; Sala et al. 2016). Cost and time effectiveness are therefore a basic requirement and underline the necessity for standardized survey routines and data processing and interpretation workflows.

Material analysis

Material analysis is a well-established field within the archaeological sciences (Gebhard 2003). Research topics are often specialized to such a degree that experts, who have been working within the respective field for a long time, are needed. This is mainly due to the enormous variety of different materials representative for human societies. In general, material analysis in archaeological sciences can be used to analyze objects produced and used by humans (and also their skeletal remains) or the chemical and physical properties of the material in which they are embedded. The latter is also referred to as geoarchaeological research (Shahack-Gross 2017). The main challenge for nearly every analysis of archaeological or archaeology related material is the basic heterogeneity of the material itself. Furthermore chemical composition often has been changed during deposition. For example, the corrosion of metals stops only when equilibrium between the surrounding soil and the embedded object is reached. This process is influenced by various parameters including soil composition, humidity and pH-value. Throughout this process the original composition of the material is changed gradually within the metal object (Gerwin and Baumhauer 2000; Neff et al. 2005). This example illustrates the complexity of the interpretation of observed phenomena.

Within this thesis two methods will be exemplarily described – secondary electron microspcopy (SEM) combined with energy dispersive x-ray spectrometry (EDX) and x-ray fluorescence spectrometry (XRF). Both applied very early for archaeological research after introduction. For the quantitative analysis of the composition of the materials both methods measure the amount of emitted characteristic x-rays but with different excitation sources and procedures.

SEM is traditionally used for the investigation of surface structures with spatial resolutions of a few nm. Within material sciences and engineering small samples - sometimes slices polished and cleaned to the highest level - are analyzed with this method. Due to the basic functionality of SEM they also have to be conductive - which can be achieved by covering the surface with gold or carbon – and must withstand high vacuum. These factors would limit the variety of analyzable archaeological samples as usual samples are comparably big, dirty, not or only minorly conductive and not suited to be placed in high vacuum. Therefore atmospheric SEM (Daniatos 1981) with unusual large specimen chambers has been established within the archaeological sciences and become state-of-the-art within the last 15 years. They are well suited for the investigation of strongly heterogeneous samples, where it is crucial to visualize the distribution of different components of a given material. SEM combined with EDX or wave length dispersive x-ray spectrometry (WDX) became a standard tool for the fast and non-invasive analysis of mainly archaeological artifacts, skeletal remains and biological material (e.g. phytolites, coprolites and archaeobotanical samples) (Hill et al. 2007); (Ollé and Vergès 2014; Martinez et al. 2005).

Whereas the material analysis provided by SEM and EDX allows the detection of elemental concentrations within the range of a few per mill, XRF has a lower detection limit within the range of ppm. Recently portable XRF (pXRF) spectrometers have been introduced within the archaeological sciences (compare also (Davis et al. 2012; Frahm and Doonan 2013). They are mainly used for the analysis of artifacts in remote areas or when artifacts and samples cannot be transported to a laboratory. Therefore pXRF is also widely applied in the studies of works of art (Viguerie et al. 2009). Besides the ability to create a small portable laboratory with fixed geometry of sample and spectrometer (Romano et al. 2005), these systems can be also applied in the field. Since the early 2010s pXRF was occasionally being applied at field surveys and at archaeological excavations. The standardized use of pXRF for the analysis of the material composition of excavated archaeological features can provide results for a closer understanding of the creation and transformation processes of the excavated deposits. It can also detect anthropogenic tracers in order to investigate the functionality of the respective feature. Finally, in analyzing the material aspect and physical properties of an archaeological feature, the results can be compared with the preliminary results of preceding archaeological (geophysical) prospection. This knowledge can be used to obtain better modelling of data gained through geophysical prospection. It also illustrates multiple benefits regarding the close collaboration of different archaeological sciences.

Integrated interpretation

Archaeological results have always relied on various sources of knowledge. In traditional approaches, the results of different methods were combined to analyze specific research questions. Results were collected mostly in order to display various properties and attributes of the archaeological record. It could be argued that data originating from different methods have been treated like artifacts in archaeology. The attempt is made to find analogies between different datasets (Garrow and Shove 2007). Based on this, these data and their respective results are compared and described as if they were artifacts. This combination and comparison of different results naturally leads to valid interpretations of the archaeological record. It works perfectly and often allows a very detailed characterization of archaeological evidence within more or less known settings. The limits of this approach are reached whenever contradictions appear. This could end in a discussion between participating disciplines over the reliability and validity of their respective results. Although it can be assumed that every discipline relies on well-defined methods, this criticism is often mentioned within scientific discussions regarding contradictive results.

Being aware of this situation, recent work has concentrated on an integrated interpretational approach of the different datasets (Neubauer and Eder-Hinterleitner 1997; Epov et al. 2016). Many publications have illustrated the demanding need for integrated analysis of the data, and for having a basic idea of possible theoretical and practical routines. Another aspect which must be taken in account is the enormous quantity of data representing archaeological information, e.g. motorized geophysical prospection, which generates an enormous amount of data. Typical GPR datasets result in volumetric data with resolutions of 8 by 4cm horizontally and 1cm vertically with a maximum penetration depth of 2 to 3 m (Trinks et al. 2009). Some datasets represent areas within the range of some square kilometers (Gaffney et al. 2012). This example illustrates that archaeological sciences have begun to deal with real big data (Torrejón Valdelomar et al. 2016). The current challenge in archaeological research is the visualization and management of these data. Since archaeological phenomena and the information derived from their analysis are always correlated with a geographical location geographical information systems (GIS) provide the widely applied basis for this. Archaeological data management is nowadays mostly based on GIS and geodatabases, whereas the wide range of GIS functionality is applied for the analysis and visualization of the data (Neubauer 2004).

The design of GIS-based archaeological information systems (G-AIS) can be optimized for an integrated interpretation of results. For example, network analysis can be done including parameters derived from topographical analysis and spatial analysis of archaeological sites (least cost path analysis). Recently software extensions have been developed regarding visualization and semi-automated interpretation concepts of archaeological prospection data (ArchaeoAnalyst) (Torrejon-Valdelomar et al. 2015) and the temporal analysis of observed phenomena (Harris Matrix composer, HMC+) (Traxler and Neubauer 2008). G-AIS set up in this way provide the possibility for the spatio-temporal analysis of the archaeological record within a 4D approach. Recently Allan´s interval algebra has been introduced as an optimized temporal concept based on the superposition of time intervals. Until lately, archaeological research has dealt with the temporal relations "earlier", "later" and "contemporary". In contrast, a time interval based approach is a complete representation of possible temporal relations of two or more processes (Allen 1983). All observed phenomena are represented through a time interval rather than a specific point in time. This 4D approach for the interpretation of archaeological data and evidence has recently been discussed within the scientific archaeological community (Drap et al. 2017). Whereas the necessity to set up a theoretical but also practical framework to handle the data four dimensionally has become obvious, recent research has dealt with the basic description of how to manage integrated interpretation. This has to result in a quantification and standardization of routines and workflows. The aim must be the record of the spatial superposition and the temporal relation of every observed archaeological entity.

Given data, also derived from material analysis and archaeological prospection, displays different properties – or aspects – of a phenomenon. To fulfil the aim of a 4D interpretation of an archaeological record, all of this data must be included. The practical framework is defined by the creation of a 4D G-AIS. Standardized routines for the integrated implementation of these data have still to be elaborated. They must depend on the principle accuracy, precision, validity and reliability[4] for a specific context of every applied method. Under these circumstances a strictly defined separation of each methodological branch is obligatory in a first step. As soon as single results are interpreted within a given context regarding their mentioned properties, they are prepared for reproducible integrated interpretation.

To summarize, the need for and the effectiveness of an integrated interpretation approach is widely accepted and state-of-the-art. Although some basic demands (e.g. 4D approach based on Allan´s

[4] It has to be clearly stated, that „reliability" is not a principal property of a method. Every well-defined method is reliable. Reliability has to be defined for an applied method within a given context.

interval algebra) and examples for integrated interpretation have been presented, a general and valid description and definition for routines is still elaborated. Described suggestions for these routines are aware of the basic need of reproducible results. The development of a standardized display of possibility and certainty of results and interpretations is another important topic to be discussed (Crema et al. 2010). Especially when results are visualized and the possible original appearance of archaeological evidence is reconstructed the hypothetical character of these suggestions must reamin evident. It is an observed phenomenon that visualized results (e.g. virtual reconstructions) manifest themselves within the perception of the scientific community (and more likely within the wide public). Therefore the indication of the hypothetical character of these visualizations is crucial. This should be guaranteed through the basic demands of traceability and reproducibility within an integrated interpretational approach.

Structure of this thesis

This thesis is structured according to its cumulative character. Several peer reviewed papers and minor articles will illustrate the demands of the integrated interpretation of datasets derived from selected methods of archaeological sciences based on multidisciplinary methodology. For this purpose the thesis will provide a short introduction into the basic characteristics of the material under investigation. Within this chapter types of different archaeological material to be analyzed by archaeological sciences will be described. For each type brief specifications regarding origin and archaeological purpose as well as context-dependent relevance will be given. A special focus will be set on the heterogeneity of archaeological material as a collective attribute.

In the next chapter methods applied to the presented research will be listed. This will be pXRF and SEM combined with EDX for material analysis and magnetic prospection techniques for archaeological prospection. A special focus will be placed on the interdependency of applied method and experimental setup[5] for the quality and possible interpretation of the results gained. Magnetic prospection will be discussed in greater detail, as the basic development of motorized systems has been undertaken throughout the last years. For a better illustration of the capabilities and range of applications of SEM in archaeological sciences a paper will be included. Within this paper an analysis of phytolites embedded in human dental calculus and their chemical extraction (dental wash technique) will be presented. This work has been done in collaboration with physical anthropology. Recently investigations in applying pXRF for the on-site measurement of soil at archaeological excavations were made. A short paper will describe a suggested workflow and interfering parameters. For every method processing procedures will be discussed in order to clarify the workflow from data acquisition, data processing and data interpretation.

[5] This includes the environmental setting and the principle character of a given archaeological context.

The final chapter will deal with the integrated interpretation of multiple datasets. For this purpose the setup and basic design of G-AIS capable of analyzing and managing big data will be described first. Two papers will be presented within this section. One paper will present and discuss the design of a G-AIS specified for the analysis of the legacy datasets of the long-term excavation at Tel el Daba/ Egypt (Bietak 1996). The other paper examines the approaches of archaeological research regarding multidisciplinary big data and their integrated interpretation on the basis of a case study run by the Ludwig Boltzmann Institute of Archaeological Prospection and Virtual Archaeology based in Vienna/ Austria. Several archaeological prospection techniques including archaeological excavations have been carried out in the area of Kreuttal/Lower Austria and provide a multiple dataset. The paper also provides information on the setup and development of motorized magnetic prospection. On this dataset approaches of integrated interpretation have been tested and developed. First results will be presented in this paper.

Finally the principle specifications of the integrated interpretation of multiple archaeological datasets based on multidisciplinary methodology will be discussed. This will include basic suggestions for a general workflow regarding data acquisition, data processing and analysis. From this, limitations of the single applied methods and the overall integrated interpretation will be derived. A focus will be set on how to achieve reproducibility of the results gained. Basic aspects of multidisciplinary research, its benefits but also its pitfalls and limits will be discussed. Within this section, two papers will be presented to illustrate the theoretical and practical framework of multidisciplinary and interdisciplinary research.

The final section will conclude with the theoretical framework for multidisciplinary and interdisciplinary collaboration of different sciences. As archaeological research must always include various disciplines, inter- and multidisciplinary collaboration principles and routines and their respective description are the fundamental requirement for accurate scientific research.

Archaeological material

General aspects

Most important for the basic selection of specific methods of archaeological sciences is a specification of the archaeological material under investigation. For this purpose three types of archaeological material can be described. Archaeological material is also characterized by the archaeological context, in which it has been found. Therefore the description of the data collection process is another important aspect to understand the origin of the multiple properties of archaeological material. Although a huge variety of these properties can be observed, principle rules regarding the spatial superposition and temporal relations of archaeological evidence are valid for the whole archaeological record.

Three basic groups of different types of material can be distinguished within this record. The first group can be summarized as finds and includes artefacts, biofacts (ecofacts) and manuports. A further group is samples derived from soil, i.e. the material in which finds can be embedded. Both groups are mostly collected through archaeological excavations or sampling. A more abstract group is represented by archaeological entities in general, such as structures and features partly hidden in the archaeological landscape. This group is mainly investigated by archaeological prospection regarding primary detection and spatial analysis. Specific physical and chemical properties of these entities are mapped in contrast to the surrounding material through the application of different sensors. Additional interpretation and analysis of results gained by archaeological prospection can be supported and examined by material analysis.

These groups vary a lot regarding size and scale. The size of archaeological material ranges from smallest artifacts and samples to whole landscapes at archaeological structure and feature level. Therefore a description of the different data sources can be based on the separation of archaeological excavations and sampling from the investigation of archaeological landscapes (landscape archaeology). Finally the basic character of all archaeological material can be discussed and illustrated. All the mentioned types of material derived from different data collection modalities display a strong tendency towards heterogeneity. Reasons for this and its influence on the applied methods and results will be presented.

Data collection and provenance of material

Archaeological excavations

Most archaeological material is still derived from excavations of archaeological sites[6]. In order to illustrate the origin and character of the revealed archaeological material basic principles regarding the excavation and interpretation of archaeological sites have to be argued. As Edward C. Harris mentioned, all archaeological sites are stratified (Harris 1979), i.e. a site is represented by a sequence of anthropogenic units. Before a site is excavated it can be presumed that a specific stratification is given. This stratification can be referred to as being "true" (see also p.209). In general two types of units can be distinguished – deposits and surfaces. They represent the stratification of a site and are therefore called stratigraphic units (SU). The difference of these two and their archaeological relevance can be illustrated as follows. When a hole is dug for a pit, the surface i.e. the boundary of this pit indicates a specific time interval. In the following the pit is refilled according to its purpose. This refilling process could be represented by a time span of any order. The immaterial surface of a feature always indicates a specific (often very short) time interval, where a relevant action took place. The analysis of the material aspects of a deposit (refill of the pit) allows the examination of formation processes (Mattheußer and Sommer 1991; Barker 1998). The deposits can provide information about the purpose and functionality of a feature. During the excavation these SU are excavated in the reverse order to their prior creation and deposition[7]. It has to be stated that this is already an interpretation of the archaeological evidence of a site. Although excavation techniques are constantly developed and optimized the true stratification[8] could be never displayed. The precision of an excavation relies first of all on the skills and experience of the excavator. This experience is related to the specific type of excavation regarding its environmental setting. There are huge differences of excavating in different types of soil (e.g. loess, sand, stony soil, etc.) and environment (marshland, dryland, mines, caves, etc.). The stratigraphic sequence derived from the excavation process represents the interpretation of the archaeological site by the excavation itself

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[6] For a critical discussion regarding the necessity of excavations and their 21th century perception please compare also Ndlovu (Ed.) "Why excavate" with contributions from Demoule J.P., Cherry J.F., Carver G., Nilsson B., Kolen J., Ndlovu N., Edgworth M., Zubrow E.B.W., Bonnie R., (Ndlovu (2011)).

[7] This is valid for stratigraphic excavations. The methodology and techniques applied for excavating archaeological evidence have been and still are sometimes heavily discussed. Within this work the focus is set on stratigraphic excavations, because they are capable of revealing 3D information of SU. Basic critics of this method include the questioned confirmability of stratigraphic sequences, as all archaeological evidence is destroyed by the excavation. It is criticized that the recorded sequence has to be trusted on and no prove for the accurateness of the results can be presented. On the other hand the necessary complete representation of an archaeological site can be only achieved in providing a stratigraphic sequence. This sequence can only rely on a volumetric record of SU, their spatial superposition and temporal relations. Archaeological sciences are an important tool to examine stratification before excavation and to classify observed SU also based on their material properties.

[8] The term „true stratification" will be discussed and defined more detailed in the chapter "discussion" in the paper "Der Dämon der Interdisziplinarität"(see p.209).

and has a hypothetical character. What can and has to be done is the most accurate documentation of the excavation process, i.e. the complete 3D recording of all SU (Doneus and Neubauer 2006). This record is the basis for a temporal analysis of the sequence (Traxler and Neubauer 2008; Neubauer 2007).

All finds and samples collected at an excavation are related to a SU. The spatial superposition of these SU is depicted by the stratigraphic sequence (also referred to as “Harris Matrix” in order to honor E.C. Harris) (Harris 1979). As this sequence illustrates the true stratification only partly, finds and samples related to a specific SU can not only be “earlier” and “contemporary” but also “later” than the time interval covered by the deposition process of the SU. This is of crucial relevance for a temporal analysis of the stratigraphic sequence. Furthermore this has to be taken in account when applying dating methods.

Landscape archaeology

Another source of archaeological material can be illustrated by the archaeological discipline of landscape archaeology. Excavations can only provide a narrowed insight into archaeological evidence and destroy it at the same time. The relation and temporal development of archaeological sites can be also interpreted at the scale of landscapes. For this purpose different parameters are examined to describe the landscape and to detect archaeological evidence. Landscape archaeology aims to interpret and analyze the spatial and temporal relations of archaeological sites and networks, such as trading routes in interaction with environmental parameters (e.g. topography, availability of resources, climatic changes, etc.) (Doneus 2013a). The archaeological material, which is examined within this context, includes superior concepts like settlement areas, cemeteries, agricultural fields, industrial zones and road network. Compared to an excavation, features and structures can be argued as finds within these areas. Like finds in deposits they can characterize the functionality and intentional use of areas. Their spatial and temporal relation can be displayed with a stratigraphic sequence. This sequence is mostly incomplete, because only limited information regarding the real spatial superposition of these entities can be derived from the archaeological record. Nevertheless the stratigraphic relations are complemented by every additional information gained through archaeological sciences.

Types of archaeological material

Finds

As already mentioned finds can be artifacts, biofacts (ecofacts) and manuports. They can provide information e.g. for dating, environmental research, use and production of the respective find and its provenance. For this purpose several methods for material analysis can be applied. Each find has to be interpreted within the context where it was found. This is mainly the location of its final deposition, which is illustrated by the stratigraphic sequence. Spatial analysis regarding the find location in respect to the surrounding structures and SU allows investigating formation processes and intentions, which lead to the observed situation. E.g. is the find deliberately placed or is it just thrown into a pit. This analysis provides also information about the temporal relation of a find and the deposit in which it is embedded. A central demand during excavation and analysis of its results is to decide, whether a find is hypothetically representative for a specific archaeological context or not. This can mostly only be done by persons experienced in the interpretation of stratigraphic sequences and formation processes and excavating itself.

Artifacts - as a subset of finds - can be characterized regarding their function (tool, jewelry, weapon, basic commodity, etc.) and the material they are made out of. Based on that, specific questions can be formulated and examined with the respective methodology. In principle artifacts are used to date archaeological context and declare its functionality. They are most often found within the context of a settlement or domestic setting in general, as offering, grave goods or within hoards. The interpretation of the value and functionality of an artifact is highly dependent on the archaeological context in which it was found. E.g. some burial objects imitating tools seem to be only produced for this purpose. If they would have been found within a different context a wrong impression of mechanical skills could be guessed.

Biofacts or ecofacts are a sub group of finds consisting of naturally grown organic material. They include botanic remains (seeds, charcoal, pollen, etc.) and animal remains (bone, teeth, horn, insects, etc.). Once they are transformed and shaped by humans, they become artifacts. Biofacts allow analyzing the environmental setting, climatic changes, food pattern, textile production and skills in medicine. An important biofact is wood. Pieces of sufficient size are perfectly suited for dating and the study of micro climatic changes (Weigl et al. 2008). Disciplines like archaeozoology and archaeobotany deal also with these finds. In most cases the species of the respective biofact has to be determined.

The last sub group are the manuports. These are finds of inorganic material, which have been intentionally moved but not transformed by humans. Archaeological sciences are only applied normally to examine the provenance.

Soil

Archaeology is first of all dealing with the analysis of formation processes. Nearly everything, which was created by humans, will be deposited, whether it is a house structure or an artifact. Most of these features and objects will be covered with soil during various formation processes. The composition and structure of this soil is therefore depicting the processes, which lead to an archaeologically documented context. Understanding an archaeological context means, analyzing the phases of creation, use and decay of a feature or structure. For this purpose different properties of the soil can be examined including micromorphology, soil chemistry, susceptibility, electric conductivity, humidity and color. Analyzable, interfering and interactive parameters are numerous.

Archaeological structures and features

Whereas structures and features can be analyzed by archaeological excavations, they are more effectively detected by archaeological prospection. It depends on the physical and chemical properties, whether one of these entities can be found by the application of a specific method. These properties have to be in contrast to the surrounding material. Seasonal changes regarding environmental settings influence also their visibility. Especially results in aerial archaeology are controlled by seasonal weather conditions. Archaeological features can cause observable differences in the vegetation cover, which is also biased by soil and weather conditions. Basic rules for optimal settings could be stated, but results rely mostly on personal experience for the right moment to launch flight missions and luck. The analysis of the physical and chemical properties of the material component of these features is crucial for closer study regarding their principle visibility (Löcker et al. 2015).

Structures and features are theoretically represented by a discrete volume or surface at a distinct geographical location. Nevertheless the determination of their spatial extent depends of the applied methods and techniques. Best confidence is reached, when the methodologically determined extent is identical to the real physical extent of the entity. E.g. solid structures (architecture and architectural parts such as columns) are represented far better, than SU such as pits or dumbs of dirt.

Archaeological prospection

State-of-the-art archaeological prospection techniques include methods from remote sensing and geophysical prospection. Recent years have seen a fast development of these techniques, of which some became already a standard tool. When the application of airborne laser scanning (ALS) was introduced as a marvelous prospection technique, also for forested areas, the ability for investigating archaeological landscapes increased dramatically (Doneus et al. 2008; Harmon et al. 2006; Doneus and Briese 2006; Barnes 2003; Challis et al. 2008). Emphasized by these first results the field of landscape archaeology was encouraged to get into the focus of archaeological research. Together with aerial and satellite imaginary these prospection techniques - to be summarized as airborne remote sensing techniques - are capable of non-invasively examining large areas for archaeological evidence. Ground based surveys include traditional survey methods like field walking and geophysical prospection techniques. Sometimes ground based geophysical prospection is also referred as remote sensing (compare also (Wiseman and El-Baz 2007). Through geophysical prospection the physical properties (e.g. density, susceptibility, electrical conductivity and resistivity, variations of the magnetic field and seismic patterns) of the subsoil are examined. Regarding archaeological prospection methods and survey routines of near surface geophysics are applied. These methods were started to be introduced as applications for archaeological prospection in the second half of the 20th century (Zickgraf 1996). Since the change of the millennium affords were undertaken to motorize measuring devices in order to allow covering larger areas ((Panissod et al. 1998; Guerrero et al. 2016; Lueck and Ruehlmann 2013; Trinks et al. 2009; Leckebusch 2005). This development became also possible, because the Valetta Treaty favors non-destructive methods for the detection and preservation of archaeological heritage.

The Valletta treaty and its implications for archaeological prospection

In 1992 the multilateral Valetta Treaty dealing with the protection of archaeological heritage was signed by the Council of Europe. The council itself was founded in 1949 and is an interregional intergovernmental organization of 47 states. One of its main aims is to promote and protect European culture. So far (April 2017) 45 members of the Council of Europe (including Austria) and the Holy See have signed and ratified the Valetta treaty (http://www.coe.int/en/web/conventions/full-list/-/conventions/treaty/143/signatures).Within article 1 paragraph 1 of the revised European convention on the protection of the archaeological heritage, the aim of the treaty is defined as "to protect the archaeological heritage as a source of the European collective memory as an instrument for historical and scientific study" (*European Convention on the Protection of the Archaeological Heritage* 1992). Within article 2 it is stressed that " archaeological reserves, even where there are no visible remains on the ground or under the water, for the preservation of material evidence to be studied by later generations" (*European Convention on the Protection of the Archaeological Heritage* 1992) have to be created. This article implicates the application of techniques to reveal hidden and so far unknown archaeological evidence. In order to preserve the archaeological heritage it is mentioned in article 3, that "non-destructive methods of investigations" have to be "applied wherever possible" (*European Convention on the Protection of the Archaeological Heritage* 1992). Excavations are planned to be only undertaken by professional institutions and authorized persons. They are clearly defined as being destructive and shall therefore include a strategy for a proper conservation, preservation and management of the uncovered evidence. Signing parties also agreed on supporting and guaranteeing the close collaboration of archaeological institutions and town and regional planners. As archaeological heritage has to be protected, development plans have to be adapted in accordance with it. This reveals the necessity of disseminating archaeological knowledge and results and therefore rise awareness for the hidden archaeological landscape. Methods and techniques have to be encouraged and funded to guarantee the prospection, detection and preservation of archaeological heritage. Keeping in mind that the archaeological heritage is under threat worldwide the Valletta Treaty underlines the awareness of the signing parties. Due to the daily rise of land use and modification of the near surface layers the proposed articles are demanding.

The protection of archaeological heritage implicates first of all its detection. Archaeology applies various techniques to reveal and investigate hidden archaeological evidence. In general one could distinguish these methods by the spatial range to be covered and whether these methods are destructive, minor or non-destructive. Although archaeological excavations can be seen as the core competency of archaeology (certainly from a public perspective) and favorite methodology throughout decades, they are destructive and leave a lot of responsibilities behind. The uncovered archaeological evidence including artifacts, human remains and architectural structures has to be preserved and managed. Excavations could only represent a much narrowed view of an archaeological site, because they are spatially limited and are usually not suited for detecting unknown archaeological evidence. Whereas they are still partly used for this purpose according to modified strategies in trenching (Verhagen and Borsboom 2009), they are certainly not suitable for the investigation of archaeological landscapes for inter site analysis.

Near-surface geophysical prospection

Archaeological features hidden in the subsurface can be detected and analyzed regarding their specific physical properties in contrast to the surrounding soil or bedrock. Whenever significant differences of e.g. electric resistivity, magnetic susceptibility, interaction with the earth´s magnetic field or density of archaeological features exist, they can be basically observed with respective methods. Ground-based geophysical prospection techniques applied for archaeology are optimized for the detection of near surface phenomena to a depth of some meters. These methods were originally designed for the exploration of natural mineral deposits and geological phenomena of the earth´s crust. They are also used for near surface surveys of non-archaeological context (e.g. landmine detection, quality control in road building, monitoring of safety embankment).

For a correct interpretation of the observed features regarding size, depth and material, basic knowledge of the involved physical parameters and the experimental setup is obligatory. The experimental setup includes the interaction of the observed phenomenon with the applied method within the specific environmental settings. The latter limit the successful usability of geophysical prospection methods. Recently the interaction of different soil parameters (humidity, conductivity, pH-value) and their impact on results are investigated (Lueck and Ruehlmann 2013; Skierucha et al. 2012). As these parameters are partly dependent on seasonal changes, preceding analysis and monitoring of the current environmental setting allows optimizing the moment for surveying a specific area. Although distinct seasons might be preferred, the surveys are also temporally limited by general accessibility of the areas. Most surveys (especially motorized surveys covering huge areas) are carried out on farmland and could be only entered on permission after harvesting, when no damage is caused. The optimization of a survey regarding the environmental settings is mostly a compromise between these mentioned aspects. It is especially challenging, when the time frame is set by scheduled construction work. In this case it has to be stated that the lack of evidence is not evidence of lack. In surveying the environmental parameters the chance for principle detection of archaeological features with a specific method can be estimated and results argued within this scenario.

Geophysical prospection techniques applied for terrestrial archaeological surveys include ground penetrating radar (GPR), electric resistivity, electromagnetic induction (EMI) and magnetics. All methods together are capable to specify permittivity, permeability and resistivity of soil. Magnetic prospection is the only passive method and has been applied mainly for the presented studies. To illustrate the huge variability and heterogeneity of soil characteristics based on physical properties basic principles for the others will be given in the following.

Ground penetrating radar (GPR)

GPR is suited for the non-invasive near surface analysis of the structure of soil and the crust of earth. High frequency electromagnetic radiation (microwave band – UHF/VHF) is used to investigate the refraction, reflection and transmission properties of the composition of layers and transition zones between them. The technology is applied for exploiting natural mineral deposits and the study of the structure of the earth´s crust in general. The inner structure of glaciers[9], bedrock, soil and underground water repositories are examined. Within the following decades GPR was not very frequently applied until the 1970s when it was started to be used for military purposes (mine detection). It was also during this time, that GPR was introduced for archaeological prospection (Vickers and Dolphin 1975). Its ability to reveal archaeological structures in the subsurface on a volumetric basis initiated huge expectations from this method. First results suggested even a paradigm change regarding the necessity of archaeological excavations. It was soon realized that "x-raying" (as this method is often compared to by archaeologists) the subsurface does not necessarily lead to a complete volumetric description of archaeological structures embedded in the subsoil. This is due to various interfering parameters regarding the environmental setting, the experimental setup (e.g. type and frequency of used antennas), the processing algorithms and filters applied for processing of the data, the visualization of the data and its final interpretation. Nevertheless recent developments regarding the processing and especially the visualization of GPR data, based on a volumetric approach, are promising to 3D model the buried archaeological structures (Herrmann 2013; Novo et al. 2010; Schneidhofer 2017).

Basic principles

The velocity of electromagnetic waves through material is dependent on the dielectric properties of the medium which is penetrated. The dielectric ε of a specific material is determined by the ratio of the capacity C of a capacitor with the respective medium inserted as an insulator and the capacity C_{vac} of a capacitor with vacuum in between.

$$\varepsilon = \frac{C}{C_{\mathrm{vac}}}$$

The subsurface is represented by a sequence of materials of a different dielectric. The dielectric determines the amount of charge, which could be stored by the respective material. Charging the material will cause a decrease of the transmission velocity of an electromagnetic wave. For microwaves in the range of 10MHz to 1GHz (maximum range of applied frequencies for

[9] One of the first GPR measurements ever being carried out was undertaken by W. Stern in 1927, to determine the depth of an Austrian glacier (Stern W. (1930)).

archaeological prospection) the velocity v is proportional to the speed of light c and reciprocal proportional to the square root of the dielectric.

$$v = \frac{c}{\sqrt{\varepsilon}}$$

The smaller the dielectric is, the faster the velocity of the microwave will be. Only in vacuum the velocity will reach the speed of light. Within a material characterized by a single dielectric, a wave penetrating through it will be stopped after a specific time of flight. If more than one material with different dielectrics is transmitted, the transmission zones or interfaces of different media cause refraction and reflection of the microwave due to the different propagation velocities (for a more detailed description of the mathematical model compare also (Goodman and Piro 2013) p. 11-36).

The amount of refraction and reflection at an interface of two different materials depends on the dielectric properties of these and the angle of incidence. GPR characterizes therefore not the material itself but the dielectric contrast of two or more materials.

A GPR system consists of at least two radar antennas, of which one is the emitter and the other the receiver of electromagnetic waves. The emitted signal penetrating the subsurface is multiple reflected and refracted. The reflected electromagnetic waves are detected by the receiver antenna. From time of flight analysis, depth information regarding transmission zones can be derived. This information is dependent on actual speed of the electromagnetic waves in the respective substructures of the soil (or bedrock).

Motorized multichannel GPR

When GPR techniques were applied for the first time systems consisted of only one pair of antennas (emitter and receiver). First attempts to use multichannel systems date to the early 1990s (Warhus 1993) but were limited by the status of the post processing of complex data and computational power. The main challenge within the following years was to develop radio antennas with comparable physical properties, which have caused interference within the first multichannel arrays. Since the early 2010s systems like that are available and have been applied successfully (Trinks et al. 2010a). As shown by Annan (Annan) a full resolution GPR system is guaranteed, when the antennas are separated by ¼ of the wavelength of the induced electromagnetic wave (cross line spacing). For an antenna emitting at an average frequency of 300 MHz this would represent a separation of roughly 25cm. This is also well in the range of the physical size of most antennas. Nevertheless some high resolution systems use antennas of 16cm width within a cross talk array. This setup provides a minimum cross line spacing of 8 cm (Trinks et al. 2010a).

Multichannel GPR systems are able to cover large areas, if respective acquisition and processing software is preconditioned. At the best this software supports also motorized surveys, which start to become frequently applied within the last years (Novo et al. 2012; Linford et al. 2010; Trinks et al. 2010a). The general setup of motorized archaeological prospection regarding positioning and survey routines will be discussed in overall in a later section (Magnetic prospection).

Data processing, visualization and interpretation

Before GPR data can be processed to generate images derived from the radargrams the raw recorded radar pulses (digitized reflections) have to be analyzed regarding the occurrence of noise and interferences. Several filters are provided for the enhancement of the signal quality and the mathematical reduction of noise. Several radargram signal processing (RSD) techniques have been described to optimize the rawdata. Some of these will be described in the following (Goodman and Piro 2013).

Most frequently used include post processing gain, which amplifies reflections from subsurface structures, and bandpass filtering. With the latter DC drift and high frequency noise can be filtered in cutting of lower and higher frequencies within a defined frequency gate range. For the processing of multichannel based radargrams spectral whitening can be applied, especially when the used antennas have different frequency responses. After filtering, pulses should be more balanced with comparable gain and visibility of smaller structures is increased. When a constant noise superimposes the raw pulses, which occurs quite often, this background can be removed in calculating the average pulse of the whole radargram and subtract this value in general. This filter has to be carefully applied, as it can create virtual features and remove existing ones. The latter occurs when longitudinal features are oriented along the line of measurement.

As GPR antennas provide mostly a broad range of emitted frequencies, a round object induces hyperbolic reflections. Migration is a filter, which adds up all energies along a hyperbola and places them on its maximum turning point. It locates the reflecting surfaces in the radargram according to their real position. As the settings of the migration filters rely on the physical properties of the subsurface, optimized settings might vary across a site, which can cause the production of artifacts.

If real small signals are hidden within the background noise, they can be accidentally removed together with this noise. In order to avoid the loss of this information, stacking (or smoothing) can be applied, which is the mathematically adding of these signals. Depending on the iteration the data can be smoothed, smaller signals amplified and the noise removed. This iterative process is limited, when quality of the radargrams is worsening again.

All these RSD techniques have in common, that they have to be applied carefully depending on the primary quality of the data. In some cases it might be even necessary to split datasets regarding to observed local differences of the composition of the subsurface within the survey area.

Once the raw recorded radar pulses have been filtered regarding RSD techniques the data can be post processed to construct GPR images. The most limiting factor for post processing GPR data is the usual enormous amount of data. Computational power seemed to stay always a bit behind the data acquisition techniques and typical time needed for postprocessing usually multiple outplayed acquisition time. Latest developments of motorized multichannel GPR introduced another leap regarding the amount of collected data. During the early days the most common visualization of radargrams was the vertical display of single lines (cross sections). Although these vertical profiles reveal already important information – also about the quality of the rawdata – a horizontal display of the data is preferable. For this purpose horizontal slices are calculated from all recorded radargrams. As these slices represent the reflection amplitudes recorded within respective time gates of time of flight analysis, they are called time slices. Once the time of flight is calibrated through the analysis of the different velocities of the propagating electromagnetic waves within the medium, the depth of the reflection amplitudes can be calculated. While the earliest visualization of GPR data with time slices might date back to 1981 (Goodman and Piro 2013) first results derived from time slices were presented in 1990 (Nishimura and Kamei 1991; Yamamoto et al. 1991). A main challenge was and still is to homogenize the volumetric GPR dataset regarding the correction of propagation velocities and mathematical interpolation of the single lines of radargram to connect the respective pulses. As this procedure also can produce artifacts and annihilate detected features, it should be reduced to a minimum. This can be achieved through accurate full-resolution surveys (cross line spacing of ¼ of the wavelength of the electromagnetic wave pulse), where "empty" areas are avoided (Grasmueck et al. 2005). Accurate navigation and positioning of the GPR system either by a line grid or with GNSS are demanding. If accurate positioning and optimal cross line spacing, which depends on the frequency of the used antennas, is guaranteed, mathematical interpolation can be reduced and even avoided. If well-positioned multichannel GPR systems are navigated carefully, they provide excellent volumetric data. Minor gaps between adjacent lines can be still interpolated (Goodman et al. 2011).

Based on these 3D GPR data time slices and cross sections can be derived. The resolution of the GPR data cube depends on cross line and in line spacing. Still the data remain very complex for geophysical or even archaeological interpretation regarding the perception of spatial relations. Zapping through the different time slices and animating this sequence is hereby a helpful tool. If the contrast of the reflections is very high, iso-surfaces (i.e. surfaces, which have a comparable refraction index) could be calculated for the volumetric visualization of observed features (Novo et al. 2010;

Zhao et al. 2015; Schneidhofer 2017). This approach supports the interpretation of the observed features significantly.

Limits

Limits for the useful application of GPR in the range of 10 to 1000 MHz are mostly linked to the composition and therefore electrical properties of the subsurface under investigation. As every material found within the earth´s crust is a composite of various materials, preceding examinations regarding the general variations of electrical properties at a specific site are preferable. Whereas variations in dielectric properties and conductivity affect GPR measurement, the magnetic permeability, which is quite constant within the materials to be considered, is of minor concern. Typical values for permittivity are within the range of 3-8 for good dielectric insulators (minerals and soils). The gaps and pores of these materials are filled basically with air and water. As water has a very high permittivity (approx. 80) it influences the applicability of GPR significantly (Annan). Very small amounts of water due to e.g. seasonal variations have a major impact on the overall electrical properties of the subsurface structures and the basic maximum penetration depth of a respective GPR system.

Electrical properties are also causing changes of propagating velocity of the electromagnetic waves. Therefore the calculated depth of a feature is related to local variations of the composition of the soil or bedrock. This can lead to a relative displacement of structures. As soon as filtering of the data is applied, this has to be done carefully, as existing features can be removed while others are created. The application of filters cannot be standardized for specific settings, but has to be improved for every situation based on geophysical expertise. Results have to be first interpreted from a geophysical perspective regarding the quality of the collected data. Geophysical interpreted and optimized 3D GPR data provides important archaeological information. Comparison with other datasets can be preferably done on the basis of geographical information systems (Leckebusch 2003).

Earth resistance measurements

A further technique to investigate the electrical properties of soil and bedrock is the measurement of the earth’s resistivity. Earth resistance measurements have been applied within archaeological context already in 1938 by Malamphy (Bevan 2000) and in 1946 by Atkinson (Atkinson 1963). Most used systems were manually operated and consist of different configurations of pole-dipole arrays. Although typical setups for resistivity measurements are very time consuming and sometimes unhandy (electrodes have to be placed by hand), the great flexibility and low asset cost guaranteed constant application for archaeological purposes. Nevertheless the development of faster and easier data acquisition routines of other geophysical prospection techniques (GPR, magnetics) shortened the usage since the early 1990s. Only lately new methods for the motorized, automated and GNSS positioned measurement of resistivity based on contact sensors have been applied. These methods evolved, because of the rising need for soil analysis in precision agriculture (Terrón et al. 2015).

Basic principles

The electric resistivity ρ equals the reciprocal conductivity of a material regarding an applied electric current. Values for the resistivity can vary from 10^{-7} Ωm for excellent conductors ($0.017 \cdot 10^{-6}$ Ωm for copper) to 10^{16} Ωm for perfect isolators (amber). As the subsurface is a composition of various materials with different electrical properties, the measurement of the local variations of the resistivity can reveal information of the substructure. When an alternating current is induced into the soil by an electrode the phase shift of the measured voltage signal can be measured at another electrode. The measured signal reflects the electric conductivity and the ability of the subsurface to store electric power and transmit it after a specific time. It equals the polarizability of the subsurface, which is also referred to as the induced polarizability (IP). Strong IP is often caused by a change from electronic to electrolytic conduction and characterizes therefore differences in humidity and porosity of the subsurface. It is possible to distinguish different anthropogenic structures, e.g. depositions represented by decomposition of organic material (wood) (Weller et al. 2006) or depositions related to iron production (slag) (Walach et al. 2011). The frequency of the applied current can be optimized to gain best contrast depending on the polarization properties of expected subsurface structures (Ullrich et al. 2007).

The measured or apparent resistivity ρ_a depends on the setup of the array of the electrodes. It can be expressed as:

$$\rho_{\mathrm{a}} = \frac{\Delta V}{I} K$$

K is the geometrical factor given by the sum of the reciprocal distances of the placed electrodes (mostly at least 4 electrodes), which induce the alternating current (positive and negative electrode) or respectively measure the equipotential at a specific place (potential electrodes). Typical setups included Schlumberger, Wenner, pole-pole, pole-dipole, dipole-dipole, gradient and gamma array. All these areas consist of minimum 4 electrodes except the pole-pole array (2 electrodes) and the pole-dipole array (1 current electrode two potential electrodes). These arrays are distinguished by resolution and sensitivity regarding noise (compare also (Dahlin and Zhou 2004). Besides the application of different arrays in general three survey techniques are used for investigating substructures: vertical electrical sounding, continuous electrical sounding and pulled array continuous electrical sounding.

Vertical electrical sounding (VES) surveys are usually carried out in a Schlumberger array, were the potential electrodes are placed at the center of the line of acquisition at a fixed distance. The two current electrodes are constantly moved with logarithmically increasing distance from the center along the line for every measurement. In moving the current electrodes away from the potential electrodes, the measured resistivity is affected by deeper structures. At larger distances of the current electrodes the distance of the potential electrodes is increased as well to reduce noise. This survey procedure is suited for the investigation of depth dependent changes of resistivity. Due to the simple configuration, a more or less horizontally layered sequence of different materials has to be expected in advance. Lateral variations of resistivity are not considerable within the backing 1D interpretational model of horizontal layers.

In order to collect 2D information of the variations of resistivity along a measurement line continuous electrical sounding (CVES). This results in profile, where resistivity values are mapped vertically. For CVES many electrodes are placed at fixed equidistant positions along a line. The electrodes are connected through a multicore cable with the ohmmeter and a switching unit to trigger different pairs of potential and current electrodes. Whereas the Wenner array is preferred for single channel VES, because of its noise suppression abilities, the moving gradient array is mostly recommended (Dahlin and Zhou 2004). Nevertheless also pole-dipole, Wenner and Schlumberger are used for archaeologically motivated CVES (Tsokas et al. 2011).To use array configurations, which are more sensitive to noise, for multichannel surveys, could be argued with the higher sampling rate and data density. The most time consuming part for CVES surveys is the manual placement of the electrodes and the connecting of electrodes to the multicore cable. As this implies a lot of walking back and forth the length of the measured profile is crucial for the survey time. The survey depth is related to the distance of the electrodes and depends therefore on the target. If the mapping of groundwater is targeted, array lengths of 300 to 360m meters are recommended. This leads to a penetration depth of 60 to 80m, with initial electrode spacing of 5m. For archaeological purposes, this spacing is much closer, which results in a higher 2D resolution and a less deep penetration depth. Usual initial electrode spacing is within the range of 0.5 to 1m, which leads to a penetration depth of approx. 4m (Tsokas et al. 2011; Martínez et al. 2015).

VES and CVES need the manual placement of electrodes, which limits survey speed. To increase the daily coverage of resistivity measurement surveys, pulled array continuous electrical sounding (PACES) was introduced in the 1990s (Sørensen 1996). With PACES a multicore cable with electrodes at fixed distances is pulled by a vehicle at a constant speed of 3km/h. The electrodes have not to be placed in the ground. The contact of the electrodes is guaranteed through galvanic contact. The system is configured for several array types. Typically this method is used for hydrogeophysical surveys (Sørensen et al. 2005).

Emphasized by the demands of precision agriculture (PA) GNSS positioned and motorized systems have been developed to also investigate areas, not only single lines. It is the aim of PA to optimize the amount of fertilizers introduced regarding the local variations of the soil. For this purpose near surface geophysical survey methods were applied and elaborated. As the depth under focus is the same as for archaeological prospection, these methods are perfectly suited for the detection of archaeological evidence. Most of the systems, which are used, consist of contact sensors, which penetrate the topsoil during measurement. In 2004 one of the first systems designed for this type of surveys – namely automated resistivity profiling (APR) developed by Geocarta (France) – was applied for archaeological prospection (Dabas 2009). Recently Terrón et al. (Terrón et al. 2015) presented the results of the VERIS system (Veris Technologies Inc., Salina, KS, USA) applied for the investigation of archaeological sites in Spain. The system holds 6 electrodes, which consist of a rotating metallic disc penetrating the ground at fixed distances. The array is configured in a modified Wenner style. It is operated at speeds of 5km/h (which is also the usual speed for GPR surveys) with cross line spacing of the tracks between 1 and 1.5m (Terrón et al. 2015).

Data processing, visualization and interpretation

For data processing a preceding quality control regarding noise and contact of the electrodes is necessary. Automated systems partly document the status of the contact of the electrodes (Møller et al. 2006). As the variation of resistivity is expected to be continuous, outliers can be automatically detected and removed (Terrón et al. 2015). A next step is to interpolate the data, regarding skipped "noisy" areas and sample points during quality control. In surveying huge areas local variations of the measured resistivity can also rely on variations of humidity. In order to trace archaeological structures and not hydrogeophysical phenomena these local variations have to be filtered in normalizing the data. Nevertheless when not the apparent resistivity is analyzed but the phase shift between applied current and measured potential, normalization would dissolve material information. As mentioned the phase shift indicates the relation of electronic and electrolytic conduction within a material and is an important property for the analysis of the composition of the material (porosity, metallic, non-metallic). Finally the data derived from line or area[10] surveys is displayed within 2D vertical cross sections or represented through 3D visualizations of classified volumes of comparable resistivity (Ullrich et al. 2007). For the analysis and interpretation of the data geographical information systems become state-of-the-art (Terrón et al. 2015).

[10] E.g. the VERIS system measures lines orthogonal to the survey direction with fixed distances of electrodes (2 current and 4 potential electrodes). Due to this setup resitivity values are only measured at two depth levels (30cm topsoil and 90cm respectively) (Terrón et al. (2015)).

Limits

Similar to GPR surveys the penetration depth of resistivity measurements depend on the inner structure of the subsoil and the resistivity contrast of the different layers. High contrast increases refraction and signal loss. The sequence of more resistive and more conductive layers is significantly influencing the penetration depth. It also depends on the selected type of array and the electrode spacing. In contrary to GPR wet conditions – at least around the electrodes – have to be preferred in order to increase electrical contact. In dry soil and manually operated surveys soil around electrodes can be watered.

A most interfering moment regarding the interpretation of geoelectrical data is the principle of equivalence. The product of conductivity and thickness of a specific layer can be determined comparably accurate, whereas separate values for conductivity and thickness are not so confidentially (Shireesha and Harinarayana 2013). Equivalence can be especially observed when a relatively thin layer is between two layers with significantly higher or lower conductivity. Recently a new formula has been presented using a combination of the real and imaginary parts of the impedance. Results have been tested on a computational basis for a simplified three layer model (Shireesha and Harinarayana 2013).

Electromagnetic induction measurements

Limiting factor regarding speed and applicability of electrical resistivity measurements described earlier is the needed physical contact of the electrodes. This is avoided in applying electromagnetic methods, which work contact-free. A transmitter coil induces a secondary electromagnetic field in the soil according to the law of induction (Neumann-Lenz law). This field is specified by the conductivity, permittivity and permeability according to the Maxwell equations and related to the induction of currents. The secondary field sums up to the primary field and is detected by the receiver coil, measuring the total electromagnetic field. The measured apparent resistivity ρ_a is reciprocal to the angular frequency ω of the electromagnetic wave and the permeability μ. This relation indicates the dependency of the frequency range on the mean resistivity of the subsoil (Piro 2009). In varying the frequency the penetration depth can be determined according to the Skin depth.

Under the assumption of the simple configuration of a homogenous soil and a uniform electromagnetic field the skin depth can be calculated based on the distribution of the respective field in the soil.

$$\frac{d^2E_x}{dz^2} - i\sigma\mu\omega E_x = 0$$

Regarding a sinusoidal variation with time of ω, the field $\overrightarrow{E_x}$ is given by:

$$E_x(z) = E_{x0} e^{-(\frac{\sigma\mu\omega}{2})^{\frac{1}{2}} z} e^{-i(\frac{\sigma\mu\omega}{2})^{\frac{1}{2}} z}$$

If the amplitude of the field equals E_{x0} divided by Euler´s number *e* the skin depth p is given through:

$$p = \sqrt{\frac{2}{\sigma\mu\omega}}$$

Although this has been derived under idealized assumptions and is purely theoretical, it clearly indicates the relation between applied frequency and penetration depth. The skin effect is responsible for limiting the penetration of electromagnetic waves and the subsequent concentration of fields and the induced currents to the near subsurface. Avoiding investigations of the deeper subsoil, this effect supports the usability of electromagnetic induction for the analysis of archaeological structures in the near subsurface (Scollar et al. 1990).

EMI systems are far easier to be motorized due to the contact free analysis of resistivity distributions within the subsoil. In changing the applied frequency depth distributions of resistivity can be mapped. From the data volumetric information of the structures embedded in the subsurface can be achieved. Visualization and interpretation techniques are similar to the methods applied in GPR and earth resistivity tomography mentioned earlier.

Magnetic Prospection

Basic principles

Magnetic prospection is a passive method as the interaction of the earth´s magnetic field with near surface magnetic phenomena is observed. The magnetic field measured at a specific geographical location is mainly dependent on the magnetic field of earth (B_E), a minor external magnetic component (1 to 3% of the total measured field), which has its source outside of earth´s environment (B_{EX}) and the magnetic properties close to the sensor. The external component of the magnetic field is induced by electric currents in the ionosphere and the magnetosphere of earth. It is mainly induced by solar winds and has therefore a daily variation regarding its intensity.

The total magnetic field varies by geographical location from 67000nT around the magnetic poles to 22800nT in equatorial regions. Three classes of temporal variations could be specified regarding frequency and amplitudes. The first class is represented by the long term variations of the main magnetic field, which are of geological relevance. Secondly daily variations basically caused by the interaction of solar wind with the ionosphere have amplitudes covering a range of 20 to 50nT. Solar eruptions could cause changes in the total magnetic field of up to 5000nT. The last class is represented by small variations (micropulsation) within the range of 0.001 to 50nT with respective periods of 0.1s to 10min (Neubauer 2001).

The total magnetic field is locally influenced by the interaction with changing near-surface magnetic properties. The Avarge maximum depth is approx. 2 m, from which significant and archaeologically relevant signals are detected. These magnetic anomalies can be of anthropogenic origin and are within the focus of archaeological prospection. In principal the anomaly must have sufficient magnetic contrast to the surrounding material, to be observable. In principle magnetic anomalies can be described by remanent magnetization and induced magnetization. The first archaeological features, which were detected, have been kilns. The high contrast of these magnetic anomalies is based on the thermoremanent magnetization of the soil (clay) during firing. Natural clay is rich in iron oxides, which are randomly oriented regarding their magnetic dipole. Normally the magnetic field is to week to cause an alignment of these particles. Only when the Curie temperature for the respective material is exceeded and the material becomes paramagnetic the magnetic moments of single components can be aligned along the external magnetic field. When the material cools down it turns ferromagnetic again with aligned Weiss domains, which causes the observed high magnetic contrast (Aspinall et al. 2009).

The other source of magnetic contrast is the induced magnetization (Aspinall et al. 2009). Soils are characterized worldwide by a huge amount of ferrimagnetic minerals, which are concentrated close to the surface (Faßbinder 2007). The LeBorgne effect describes the rapid decrease of ferrimagnetic minerals with depth. Susceptibility can be up to 100 times elevated within the first 30cm of the soil than in 1m depth (Zickgraf 1996). Le Borgne was also the first, who observed the enrichment of maghemite through heat (fire). This natural stratification of ferrimagnetic minerals can be disturbed by external processes, such as accumulation and erosion, and through human influence. An archaeological site is characterized by an anthropogenic local rearrangement of parts of the natural stratification of the respective area. Areas, where the natural stratification has been disturbed, can be detected by the local changes of the magnetic field due to the spatial variations of ferrimagnetic properties of the soil. Nevertheless archaeological features such as postholes and pits are also magnetically visible within soil providing very low contrast regarding the enrichment of maghemite such as loess. In this case, the magnetic contrast of archaeological features and the surrounding soil is based on magnetite. This magnetite originates from bacteria, which use it embedded in their cells for orientation. These bacteria are present in composting processes of organic material usually expected in postholes and pits. After dying off, the magnetite remains in the respective archaeological features and induces the observed interference with the total magnetic field. (Faßbinder 2007).

Together with greigite, maghemite and magnetite are the cause for observing archaeological structures due to their magnetic contrast. The analysis of genesis and transformation of these minerals is crucial for a correct interpretation of magnetic anomalies. This includes also the study of other soil parameters such as moisture. Detailed knowledge and preceding studies of principle magnetic and geochemical properties of soil are crucial, if a preliminary assessment of possible results is requested (Faßbinder 2007).

Experimental setup

In archaeological magnetic prospection, respective magnetic properties of near-surface features, which can be of anthropogenic origin, are investigated. These magnetic anomalies – and also the respective measurement systems - influence the total magnetic field (B_E+B_{EX}), which underlies temporal variations with different rates. The variations are of a comparably larger magnitude than the local changes of the total magnetic field caused by magnetic anomalies with archaeological background. In order to detect these small changes the temporal variations must be suppressed. The experimental setups, which have been established, will be presented in the following.

Variometer

For this setup one magnetometer is placed at a fixed position at a specific height, while other magnetometers are moved at a constant distance over the surface. In subtracting the respective signals, the temporal variations of the total magnetic field are eliminated. For this setup accurate synchronization of the base magnetometer and the moving magnetometer(s) must be established, which can be unhandy when physical connection is needed. Anomalies embedded in the near surface detected well and larger anomalies (e.g. paleochannels, geological structures) are still observable. This could also cause problems, if the archaeological anomalies are located in very inhomogeneous soil. In this case a setup is desirable, which flattens these local variations of changing magnetic properties superimposing the weaker archaeological features.

Gradiometer

For the gradiometer set up the reference magnetometer is moved together with the other sensors. For this purpose several magnetometers can be arranged at two or more different levels. With this setup local variations due two larger magnetic anomalies and heterogeneity of the near surface are also subtracted and filtered. The distance of the magnetometers of the lower level to the surface and the distance between these and the reverence sensor is determining the resulting signals. The lower level sensors are usually placed 30 to 50 cm above ground, whereas the reference sensor is at a distance of 50 to 200 cm. The optimal settings are due to the magnetic environment (motor way, electric powerline and fences), the expected intensity of anomalies and the contamination of the area with recent iron parts. For example, local magnetic noise induced by electric power lines can be suppressed in decreasing the distance of the reference sensor (Neubauer 2001). The gradiometer array is commonly used for archaeological magnetic prospection.

Electronic bandpass filtering

Another option to filter high frequency variations due to power lines or micropulsation is applying electronic bandpass filters. Some magnetometer processors provide filtering in the range for 0.7 to 2 Hz (Becker 2001) up to 50 Hz (Picoadas and Förster). The diurnal magnetic variations can be filtered through the calculation and differentiation of the mean values of total measuring lines (Becker 2001).

Magnetometer probes

Magnetometer probes applied for archaeological prospection include proton free-precision magnetometers, electron spin-resonance (Overhauser) magnetometers, cryogenic SQUID (superconducting quantum interference device) magnetometers, fluxgate magnetometers and alkali vapor optically pumped magnetometers. As the latter two are mainly used by the LBI ArchPro and have been applied for the presented work, a description of the respective functionality will be limited to these magnetometers.

Fluxgate gradiometer

Fluxgate gradiometers or Förster probes have been introduced 1936 by H. Aschenbrenner and G. Goubau (Geyger 1964) respectively by Förster 1937. They have been also used airborne for military purposes in World War II and for geophysical prospection (plate tectonics) soon after the war.

A fluxgate gradiometer consists of a highly permeable nickel-iron alloy core, which is surrounded by two coils. The primary coil magnetizes the core with an alternating applied electric current and constantly leads to periodic magnetic saturation with respective magnetic field vectors oriented in opposite directions. With a neutral magnetic background the electric current, which is induced in the secondary coil, is of the same amount as the current applied and in phase. An external magnetic field H_{ex} produces a magnetic flux B in the core, depending on the size of its cross section A, which is added to the induced flux by the alternating current. The voltage V_{sec} can be measured through the secondary coil dependent on the amount of windings n:

$$V_{\text{sec}} = nA\frac{dB}{dt}$$

Is an external magnetic field present, the component oriented along the direction of the main axis of the fluxgate sensor is responsible for the magnetic flux in the core. It is directly related to the cosine of the angle between the axis of the fluxgate and the field. The flux is gated, when the core is highly permeable (Scollar et al. 1990).

In order to determine the total present field, an array of three fluxgates orthogonally arranged in all directions is needed. If only local variations of the magnetic field are to be examined, two vertically arranged fluxgates with inversely arranged windings of the coils are used to measure the vertical component of the total magnetic field. If this is the case, the amplitudes of the measured signal are anti-phased. Slight variations gained through tilting of the whole probe are therefore compensated. Nevertheless the directional dependency of fluxgates can be the cause of noise.

Fluxgate sensors are best suited to operate in a gradiometer configuration. Their maximum sensitivity is approx. 0.1 nT (Aspinall et al. 2009), which is sufficient for many archaeological magnetic surveys. Typical frequencies for measuring range from 30 to 50 Hz with a maximum of 200 Hz. Compared to other sensors asset costs are rather low (Neubauer 2001). A further advantage is their ability to suppress external magnetic and electromagnetic disturbances, which enables operation within a noisy environment. The operation in the gradiometer configuration also filters low lying magnetic anomalies and enhances the detection of features closer to the surface with lower magnetic contrast (Scollar et al. 1990). Although older models might have a significant magnetic drift, caused by thermal and mechanic properties of the sensor, values can be corrected by later processing and filtering of the data. As I. Scollar stresses, “if the anomaly strengths sought are greater than 0.5 nT, speed of operation important, and disturbances level high, then the fluxgate gradiometer is probably the best instrumental choice (Scollar et al. 1990)”. Fluxgate gradiometer sensors are therefore best suited for motorized magnetic prospection, first of all because of their ability to suppress noisy magnetic and electromagnetic environment.

Optically pumped cesium gradiometer

This magnetometer type is based on the physical principles described by the Zeeman Effect, the circular polarization of light and the behavior of rotating magnets exposed to an external magnetic field. To illustrate the functionality of an optically pumped cesium gradiometer basic principles of physics must be studied.

When spectral lines split up caused by an external magnetic field, this is referred to as Zeeman Effect. Electrons in the atomic hull can be excited by an external radiation to higher discrete energy levels. According to the interpretation of quantum mechanics, they only emit energy during transition from higher to lower excitation levels. If they fall back into the ground state the respective energy difference $\Delta\mathrm{E}$ of the two levels is emitted. This is directly correlated to the respective pulsatance ω with ħ as Planck´s constant.

$$\Delta\omega = \frac{\Delta\mathrm{E}}{\hbar}$$

A basic physical property of electrons in the atomic hull is their respective angular moment. This can be also illustrated by a schematic atomic model (see p.58).The total angular momentum of an electron $\vec{\mathrm{J}}$ consists of the orbital angular momentum $\vec{\mathrm{L}}$ and the angular momentum of the spin $\vec{\mathrm{S}}$ given by quantum mechanics.

$$\vec{\mathrm{J}} = \vec{\mathrm{L}} + \vec{\mathrm{S}}$$

Most important is that the total magnetic moment being a vector has a discrete orientation. If an external magnetic field is applied a precision of the total angular momentum is caused. This can be compared to a spinning top. If no external force is interacting, it simply rotates. As soon as a force is applied orthogonal to the rotation axis, the rotation axis is shifted out of the center and starts to rotate around the former axis. The vector in the direction of the new rotation axis is circular moving along the surface of a cone. This movement is called precession.

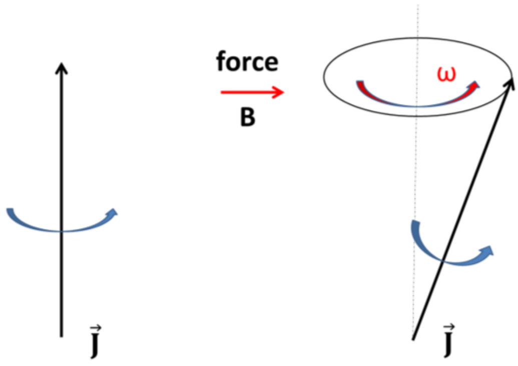

Figure 2: Precession of a rotation axis induced by an external force (© M.Kucera).

If the force applied is caused by an external magnetic field, it is called Larmor precession with the pulsatance ω_L and is directly to the magnetic field B and the gyromagnetic constant γ, which is the ratio of the charge and the mass of an electron.

$$\omega_{\mathrm{L}} = \gamma B = \frac{e}{2m_{\mathrm{e}}} B$$

Keeping in mind that the pulsatance is related also to ΔE, this results in

$$\Delta \mathrm{E} = \hbar\gamma\mathrm{B}$$

This illustrates the dependence of the energetic difference of the discrete energy levels on the applied magnetic field. When a magnetic field is applied the possible energy levels including the ground state split up according to the intensity of the magnetic field and the Zeeman Effect.

Optically pumped magnetometers use as excitation material elements of the alkali group, as they have only one valence electron, i.e. only one electron in the outer atomic shell. The material is placed in a glass cell, which is heated to vaporize the metallic element. Cesium has the advantage that it vaporizes at a comparably low temperature of 22°C, which is sufficient to produce a pressure of 10^{-6} mm Hg (Scollar et al. 1990). This vapor initially consists of Cs atoms in a single ground state as long as no external magnetic field is applied. A lamp containing also Cs at higher pressures than the Cs in the glass cell is illuminating the glass cell. The Cs in the lamp is glowing due to an applied high radio frequency field. After passing through a polarization filter to produce circularly polarized light, it is penetrating the glass cell, exciting the Cs vapor and finally conducted onto a photo cell outside the glass cell. Possible discrete energetic levels are being filled with the excited electrons, which immediately fall back into the ground state emitting radiation. This ground state is also split up into two discrete energy levels as soon as a magnetic field is applied and is strictly related to the amount of this magnetic field. The Cs light illuminating the glass cell does only excite the lower of these two states, as it can only resonate with this state. Consequently the lower energetic level will see a constant decrease of electrons until it is completely depleted. The radiation emitted by the electrons, which fall back into the ground state, is omnidirectional and does not contribute to the illumination of the phot cell. As soon as the lower ground state is completely depleted the penetrating radiation can directly pass through onto the phot cell. To repopulate the lower energetic ground state and to read out the ΔE , which is realted to the applied magnetic field, a coil is wrapped around the glass cell. An alternating current is applied and its frequency constantly increased until it copies the frequency, necessary to resonate with ΔE. At this moment absorption is reestablished, which is noticed through the signal detected by the photo cell. Form the applied frequency the magnetic field is calculated (Scollar et al. 1990; Aspinall et al. 2009).

This type of magnetometer measures the total magnetic field and can be operated in variometer and gradiometer configuration. It is also applied for the duo-sensor method (Becker 2001). It is highly sensitive (0.01 nT) and therefore suited for detecting low magnetic contrast features (Becker 1995; Neubauer 2001). Compared to the fluxgate sensors it is expensive and needs more electric power. A complete system consisting of the magnetometer, the data loggers and the power supply is very heavy. In respect to the excellent sensitivity of these magnetometers the construction of supporting carts is very sensible regarding the use of non-magnetic material and magnetic fields induced by electric currents in power and signal cables.

Data acquisition

In general magnetometers must be moved at a constant distance to the surface to record the local variations of the total magnetic field resulting in a grid of magnetic values. The resolution of the grid must be optimized for the detection of archaeological features. Within the last years, most data is collected with a cross line spacing of 0.25 m, which has been established as a standard for fluxgate sensor surveys. In-line spacing depends on the sampling rate and the measurement speed. The latter became more important since the introduction of motorized magnetic prospection. The sampling rate is mostly limited by the type of data logger and magnetometer.

Today the application of multi-sensor arrays became also a standard for archaeological magnetic prospection. First systems satisfyingly operating with 2 to 6 sensors operating at fixed positions were introduced in the 1990s (Zickgraf 1996; Neubauer 2001; Becker 1995, 2001). With multi sensor arrays consisting of highly sensitive optically pumped cesium magnetometers the high resolution recording of even faint archaeological features became possible. All constructed carts and arrays were carefully planned in using only non-magnetic material. Operators of devices were strictly asked to wear only non-magnetic clothing (Neubauer 2001).

Most important for an accurate survey is the correct spatial placement of the single measurements. The positioning can be solved by defining grids, which can be measured in alternating equidistantly walking or pushing a cart up and down. These mostly quadratic but also rectangular grids can vary in size depending on the used arrays, sensor configuration and local topography. Grid size ranges from 20 by 20m (Becker 1995) to 40 by 40 m (Neubauer 2001). Whereas the cross line spacing can be controlled by the placement of lines, the inline spacing is mostly triggered by an odometer or simply in keeping constant pace. Finally the grids are georeferenced in measuring the absolute global coordinates with geodetic equipment (totalstation, differential GPS, etc.). The georeferencing is absolutely necessary to guarantee reproducibility of the data and comparison with other datasets.

Recent developments in applying RTK (real time kinematic) GNSS positioning allow measurements without placing a grid. With an accuracy of 1 to 2 cm the position of the magnetometers can be determined. Systems operated in the RTK-mode can be also navigated based on the positioning information. If the geometry of the magnetometers and the RTK-receiver is clearly defined and fixed, this is the most accurate operation mode for data acquisition. For analysis and processing of the data the data string generated by the RTK-receiver (mostly positions in global coordinates per second) must be correlated with the magnetic data string. For this purpose a time stamp generated from the GNSS signal is fed into the magnetic data string. A disadvantage of this positioning technique is that in contrast to earlier demands more magnetic parts and parts which induce magnetic fields and electromagnetic interference are placed close to the sensors.

Data processing and visualization

Data quality

Data quality is mainly influenced by noise and positioning accuracy. The source of noise is manifold and can be classified into random and coherent noise. Whereas the latter can be reduced by filtering processes, random noise limits the sensitivity of the instrumentation and decreases the data quality.

Typical random noise includes instrument noise, cultural or environmental noise, operator noise (Aspinall et al. 2009) and mechanical noise. In this respect random noise has to be avoided already during measurement. Instrument noise can be only reduced by monitoring the data quality and physically changing respective parts. For example noise generated by fluxgate sensors increases over time due to mechanical vibrations caused by the daily survey routines. These temporal changes of noise levels must be monitored for each sensor to maintain respective sensors on time.

Random cultural noise can cause major loss of data quality, if it starts to occur during measurements. Therefore a monitoring of the data quality during measurements is crucial. For example an electric fence or power line close to the survey area could be switched on during the measurement. Without monitoring or at least occasionally controlling the quality of the data, a whole day´s work can be lost. To limit the operator induced noise is mainly important for manually carried or pushed sensor arrays, as the operator and therefore all magnetic parts carried, are moving close to the sensors. As mentioned earlier, operators clothing has to be non-magnetic. This can be checked easily before measurement in moving close to the sensors and monitor respective signals induced by the operator´s movement.

A major and avoidable loss of data quality is due to mechanically caused vibrations of the sensors during a measurement. Sensors have to be moved as smooth as possible over the surface. The roughness of the surface is therefore also and indicator for a given data quality and needs to be recorded. The status of an agricultural field can result in drastically reducing the survey speed in order to guarantee data quality. Reduction of mechanically caused vibrations especially for motorized systems spares also the single components of the system.

Another source of irregularities of recorded magnetic values is the changing distance of the sensors to the surface. Keeping in mind that the magnetic field decreases with the cube of the distance, already minor changes have major influence especially on faint anomalies. This sort of noise can be reduced by an optimized survey strategy (e.g. measuring in the ploughing direction).

In reducing random noise already during the measurement, data quality can get in conflict with survey speed. Nevertheless, if survey speed is necessary, e.g. if construction work is planned for the respective survey area or the area to be prospected is huge, and a loss of data quality has to be accepted, this can be argued. Especially through the development of motorized prospection devices it becomes possible to cover large areas and detect archaeological features at a large and inter site scale. If archaeologically relevant features are detected, which have to be observed in greater detail, this can be done additionally. This two-step planning of archaeological surveys can save time and costs.

Coherent noise can be instrument, diurnal, soil, cultural, geological or operational noise. In contrary to random noise, its interference can be partly mathematically reduced and sometimes even avoided, if the source and type of the coherent noise is identified by primary also statistical data analysis (Neubauer 2001). Some of this noise can already be eliminated by the choice of the experimental setup. For example, the diurnal noise can be removed in operating with a variometer or gradiometer configuration (Aspinall et al. 2009). Through expert-biased data processing a reduction of this type of noise can be achieved.

Processing

During processing noise is reduced and errors based on spatial displacement of data are reduced and optimized. In this respect, a main aspect of magnetic data processing is correlating positioning and magnetic data. This procedure depends on the type of positioning, as mentioned earlier. It has to be optimized for the respective survey system, survey environment and to the expected archaeological features to be analyzed. Especially filtering options, which can remove noise and enhance the visual appearance of a magnetogram, i.e. the visual display of the measured magnetic values in a 2D raster, can also erase archaeological features. On the one hand the geophysical and archaeological interpretation of not corrected raw data is not preferable, as the interpreter's perception of archaeological features and pattern is disturbed by noise and fuzziness of uncorrected magnetograms (Neubauer 2001). On the other hand every processing of archaeological magnetic data has to be expert-biased and related to the given circumstances (experimental setup, used sensors, magnetic noise and background, observed archaeological features, expected location of these features regarding depth, type of expected magnetic anomalies, shape and orientation of anomalies, etc.). From this knowledge also automated data preprocessing can be derived (Eder-Hinterleitner et al. 1996). In this respect, the applied filtering has to be documented to guarantee reproducibility of the displayed results.

Based on constant monitoring and maintenance of the survey systems, respective instrumental noise can be removed, if it is coherent. Sometimes the origin of a coherent noise is rather hard to detect. For example, magnetic data collected with a motorized system (eight sensor fluxgate array towed by an ATV), showed coherent noise. After controlling the mainly affected sensors, a magnetic particle in one of the wheels close to the sensor was found, which has been already embedded during production of the wheel. This illustrates the huge sensitivity of magnetic systems regarding uncontrolled magnetic contamination.

Often a displacement of magnetic data can be observed (Neubauer 2001). This especially happens, when the positioning failed or accuracy of positioning was low. When positioning is based on GNSS, satellite loss could be the source of bad positioning. In this case the missing locations can be reconstructed in interpolating coordinates of the GNSS data string. This interpolation method works accurately, when the measurement direction and speed have not changed.

The major amount of magnetic noise is induced, when systems are motorized, by the towing vehicle, positioning system and wiring. For example, if the towing vehicle (ATV) is placed at a distance of 8m from the sensors, only the geographical orientation of the whole system (sensor array and ATV) causes magnetic variations in the range of some nanotesla. If the system is towed straight this also directionally dependent interefnce can be filtered. If the ATV is moving relatively to the sensor array still causing changes of some nanotesla, filtering is more difficult. If the overall geometry is stable, i.e. the single components are not relatively moving to each other, noise can be filtered and reduced (Hinterleitner et al. 2013).

After physical noise and displacement errors have been reduced respective magnetograms can be enhanced to guarantee an optimized visualization of the magnetic data.

Visualization

For the visualization of magnetic data the most common type is the representation of magnetograms by gray-scale (Aspinall et al. 2009). It proved to be the most readable and interpretable format for magnetic anomalies, as the visualized data represent a value range. The human eye is most sensitive to distinguish different shades of gray rather than gradual color display. The visual enhancement of these magnetograms is related to the basic principles of image enhancement in general. The overall aim of this procedure is to optimize the contrast of magnetic anomalies. A constant comparison of input and results must be undertaken, to avoid data loss. Some enhancement processes (mean filter) can also erase features of archaeological interest. For this purpose a principal knowledge of possible observable archaeological structure and features as well as geophysical experience regarding the processing of magnetic data is crucial. As the type of visualization significantly supports the geophysical and archaeological interpretation of the observed anomalies a flexible adaption is desirable for the interpretation process itself. For the later integrated interpretation of multiple datasets data format compatibility has to be guaranteed.

Motorized magnetic prospection

A detailed description of the design of motorized magnetometers developed and tested by the LBI ArchPro is provided within the paper “Multi-method archaeological prospection and integrated interpretation investigating the Kreuttal area in Austria” (pp.157). Besides the technical aspects daily routines of data acquisition are described and first results presented.

Material analysis

Within the following section two well-established analytical methods for material analysis will be described regarding exemplary applications for archaeological material: Secondary electron microscopy (SEM) and portable x-ray fluorescence spectroscopy (pXRF). With both methods a wide range of different materials can be examined including organic and inorganic specimen, artifacts, ecofacts and biofacts. The huge diversity of materials regarding their physical and chemical properties and their origin from various archaeological contexts is a unifying character. This results in an often very specific treatment of data acquisition and interpretation. An important biasing factor is the sampling strategy and sample preparation.

This section will be mainly based on published and submitted papers except for a short methodological description of SEM and basic principles regarding the physical background of characteristic x-ray emission.

Secondary Electron Microscopy

Scanning Electron Microscopes (SEM) provide a reliable technique to investigate the microstructure and chemistry of various materials, organic as well as inorganic ones. Thus they are widely used in different fields of research. The main difference to a normal microscope is that electrons are used instead of photons to produce a picture of the surface of an object. By using electrons it is possible to achieve 100 times higher resolutions than with a normal microscope depending on the analyzed material. The electrons initialize different reactions on and in the material. The products are detected and transformed into signals, which are used to image the surface of a sample and achieve chemical information on the material.

Figure 3 shows the main components of a SEM (Leo EVO 60 plus). The electron beam is generated by a Wolfram Filament in high vacuum (10^{-6}mbar) and accelerated to energies between 1 and 30kV. In the following sections the beam is focused to a diameter between 1 and 100nm using electrostatic lenses (first and second condenser lens). It is carrying a current in the range of a few pA to several µA. The focused beam has to pass an objective lens (aperture) with a diameter of 20µm or 30µm. Scanning coils deflect the beam over a defined area of the specimen, which provides imagery and chemical information about the scanned area.

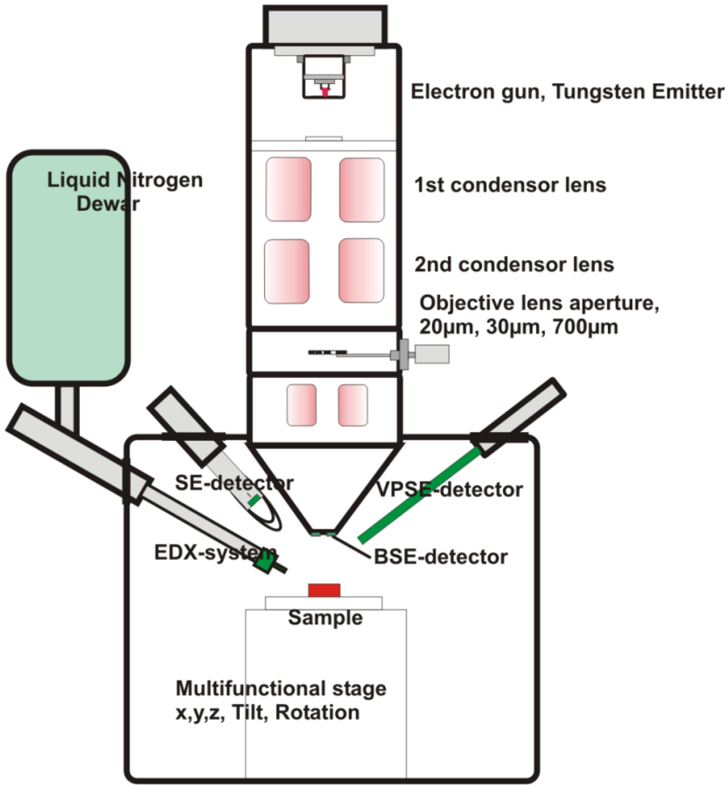

Figure 3: The main components and detectors of a VP-SEM with an EDX-system (Leo EVO 60plus, Zeiss)(©M.Kucera).

Energy dispersive X-ray spectroscopy (EDX)

Penetration of electrons in a solid-state material leads to several interactions. It is possible to distinguish between elastic and inelastic interactions. First the primary electrons (PE) of the beam can interact elastically with the atoms of the specimen. They are scattered at the atomic nuclei due to the Coulomb interaction at small angles (2-3°) mostly, but sometimes also at angles up to 180°. These backscattered electrons (BSE) have nearly the same energy as the PEs and are detected with a semiconductor detector (BSE-detector). This detector can also be referred to as a four quadrant backscatter detector (QBSD). Keeping in mind that the cross-section of elastic scattering is proportional to Z^2 (Z is the number of protons in an atomic nucleus) it is obvious that the intensity of the BSEs depends on the material of the specimen. Thus it is possibly to analyze the distribution of elements scanning over the surface of a sample. Regions with heavier elements show a higher intensity of BSEs.

In inelastic processes a part of the kinetic energy of the impinging electrons is transferred to potential energy by excitation of vibrational or electronic states of the target atoms. Electronic levels can be ionized, a process which generates electrons. In fact the PEs push electrons out of the atomic electron shells of the target atoms, which are called secondary electrons (SE). Having only low kinematic energies of about 10eV (compared to the BSE with up to some 10keV) a potential of several 100Volts is necessary to accelerate the electrons for detection with a scintillator detector (SE-detector). The lateral resolution of SE-images is about 3nm compared to 1µm with the light microscope. The reason for this is the fact that the detected SEs come from an only 10nm thick surface layer where the diameter of the primary electron beam is hardly widened.

The SEs leave holes in the inner orbitals of the atoms (see Figure 4). These holes are refilled with electrons from higher energetic levels of the same atom. The energy difference gained in this transition is dissipated from the atom by emission of either an X-ray photon or an Auger electron. The energy of the emitted X-rays depends on the energetic difference between the binding energies of the two levels involved.

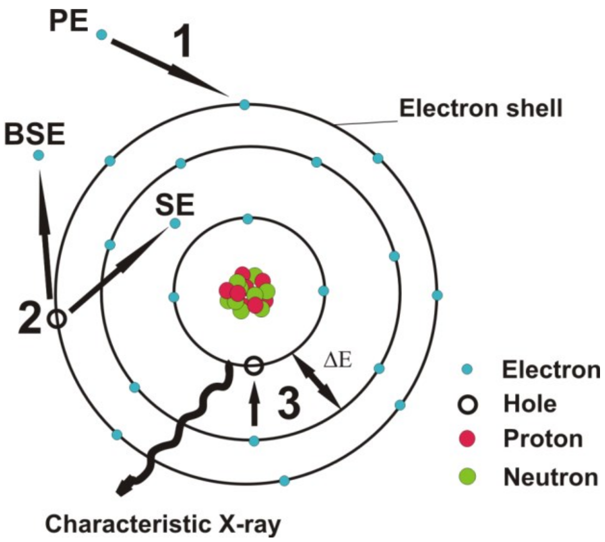

Figure 4: Schematic atomic model; Characteristic X-ray emission (©Kucera).

Typical energies for characteristic X-rays are within 0.05 to 30keV. For the measurement of the energy and the intensity of the characteristic X-ray spectrum, energy-dispersive and wavelength-dispersive spectrometers are used. With an energy-dispersive spectrometer (EDX) it is possible to simultaneously measure the intensities of all elements from B to U. The X-rays are detected from a semiconductor detector, which converts the single photons into electric pulses. A typical spectrum shows peaks at different positions, which define the energy of the x-rays and thus the sort of the elements. The height of the peaks correlates with the amount of the element. This method provides quantitative analytical results with a relative accuracy of less than 1%, while the detection limits are in the order of 0.01 to 0.1% of a distinct element.

Atmospheric secondary electron microspcopy (aSEM)

Analyzing a material with an electron beam causes not only the described effects but also charges the specimen, which is no problem if the material is conductive. In archaeology a lot of the examined artifacts are not conductive, such as bone, ceramics, textiles and other organic samples. One possibility is to coat these samples with a conductive layer like carbon or gold. The other is to work in a low vacuum mode. Atmospheric SEM[11] facilitate to discharge the sample in ionizing the surrounding gas-molecules. A second benefit is that sensible samples must not be imposed to high vacuum, which can cause damage. Due to the spreading of the electron beam in the low vacuum the limit of high quality magnification is decreasing, as the pressure in the sample-chamber is increased. Still magnifications in the range of 5000x to 15.000x revel greater details, than achievable with a light microscope.

[11] Also referred to as atmospheric or environmental SEM.

PAPER #1: Rasterelektronenmikroskopie in der Archäologie - zum Einsatz naturwissenschaftlicher Methoden in der Archäologie – Teil 2

Preamble

The following paper shall illustrate the huge variety of archaeological samples and material. When dealing with heterogeneous samples, the combination of imaginary and chemical analysis as provided by secondary electron microscopy (SEM) is a major advantage. Another important aspect, which is discussed within this thesis, is the multidisciplinary demands for a successful interpretation of the observed phenomena. This implicates the close cooperation of scientists from different disciplines and can be argued as training in interdisciplinary collaborations. A preliminary basic understanding for the respective disciplines is crucial or has to be at least developed during the first attempts of an interpretation of the derived data.

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Abstract[12]

The demand of combining different methods and techniques in order to gain new knowledge is obligatory for archaeological research. The increasing amount of methods provided by archaeometry and other disciplines implies constant examination with benefits and pitfalls, and the respective methodological development of these techniques. Only in observing and arguing these developments, the reliable application of different scientific methods for preliminary specified archaeological research questions can be achieved to test archaeological hypotheses. One of these methods being used to examine archaeological research questions is secondary electron microscopy (SEM). Modern atmospheric SEM (aSEM) allows the non-invasive investigation of even non-conductive samples. No special specimen treatment is necessary. This paper aims to specify the operation mode of an atmospheric SEM optimized for different non- or minor conductive samples.

[12] The English abstract is not included in the original publication.

Additionally limits of this methodology will be discussed regarding the specific characteristics of archaeological samples and material. This will be illustrated with respective application examples.

Einleitung und Motivation

In der Archäologie ist wie in kaum einer anderen Wissenschaftsrichtung die Kombination verschiedener Methoden und Techniken ein unerlässlicher Schritt zur Erkenntnisfindung. Gerade aber die steigende Vielfalt dieser Methoden verlangt eine konsequente Auseinandersetzung mit deren Möglichkeiten aber auch mit ihren Grenzen. Nur so ist es im Einzelnen möglich, Fragestellungen zu formulieren und Aspekte im Rahmen archäologischer Theorien zu klären. Die Rasterelektronenmikroskopie ist eine von vielen Methoden, die in den letzten Jahren für die Interpretation archäologischer Fragestellungen große Bedeutung erlangt hat. Die Weiterentwicklung und Verfeinerung der Messmethodik erlaubt nunmehr auch nicht leitende Proben, wie sie ja zu einem Großteil in der Archäologie zu finden sind, zerstörungsfrei und ohne Veränderung und Vorbehandlung des Probenmaterials schonend zu untersuchen. Die vorliegende Arbeit soll einerseits ergänzend zu dem bereits erschienenen Beitrag (Mehofer and Kucera 2005) die Funktionsweise eines Rasterelektronenmikroskopes (REM), das in einem speziell für nicht leitende Proben bestimmten Modus betrieben wird, erklären. Andererseits soll zusätzlich zu einigen Anwendungsbeispielen auf die prinzipiellen Möglichkeiten aber auch die Grenzen dieser Methode hingewiesen werden und der Umgang mit potentiellem Probenmaterial thematisiert werden.

Atmosphärische Rasterelektronenmikroskope

Die Elektronenmikroskopie wurde bereits in den 30er Jahren von Ernst Ruska und Max Knoll entwickelt (Ruska 1979). Elektronen werden durch magnetische Linsensysteme fokussiert und zur elektronenoptischen Vergrößerung von Oberflächen benutzt. Geladene Teilchen wie eben auch Elektronen werden von magnetischen Feldern in gleicher Weise abgelenkt wie Photonen, also Lichtteilchen, durch optische Linsensysteme in einem Lichtmikroskop. Die ursprüngliche Bezeichnung eines Elektronenmikroskops nämlich „Übermikroskop“ deutet schon darauf hin, dass eine bis zu 100fach stärkere Vergrößerung als bei einem herkömmlichen Lichtmikroskop erreicht werden kann, da Elektronen eine deutlich niedrigere Wellenlänge, bzw. höhere Energie aufweisen als Photonen. Ernst Ruska erhielt für seine Arbeit 1986 den Nobelpreis für Physik.

Der so auf einen Punkt gebündelte Elektronenstrahl wird nun durch ein weiteres Linsensystem periodisch über einen ausgesuchten Ausschnitt der Probenoberfläche gelenkt und führt dort zu verschiedenen Wechselwirkungen. Der schematische Aufbau des am VIAS (Vienna Institute for Archaeological Science) verwendeten Rasterelektronenmikroskops (Zeiss EVO 60 XVP) ist in Abbildung 1 (see Figure 3, p.58) dargestellt. Die Detektoren erfassen die einzelnen Produkte, die aus der Wechselwirkung des Elektronenstrahls (Primärelektronen, PE) mit der Materie des Probenmaterials resultieren, wie in Abbildung 2 (see Figure 4, p.59) ersichtlich ist[13]. Treffen Primärelektronen (PE) auf die Elektronenhülle eines Atoms (1), so können sie entweder rückgestreut werden (back scattered electrons, BSE) oder Sekundärelektronen (secondary electrons, SE) aus der Hülle herausschlagen (2). Die so entstandenen Leerstellen werden von Elektronen aus energetisch höheren Bindungszuständen nachbesetzt (3). Der Energieunterschied dieser Bindungsniveaus einzelner Schalen (K,L,M-Schalen) ist charakteristisch für jedes Element und wird bei Nachbesetzung der Leerstellen („Löcher“) als charakteristische Röntgenstrahlung abgegeben. SEs werden zur Oberflächendarstellung bis zu einer 100 000fachen Vergrößerung benutzt. Die direkt proportionale Abhängigkeit der Intensität der BSEs von der Masse der getroffenen Atome des Probenmaterials wird zur Darstellung des Materialkontrastes verwendet. Beide Detektionssysteme zeichnen sich durch eine enorme Tiefenschärfe aus, was vor allem auch bei geringerer Vergrößerung ein weiterer Vorteil gegenüber der Lichtmikroskopie ist. Die Detektion der charakteristischen Röntgenstrahlung erlaubt schließlich noch eine qualitative und zumeist auch quantitative Bestimmung der im Probenmaterial enthaltenen Elemente. Im konkreten Fall wird die Röntgenstrahlung von einem energiedispersiven Spektrometer (EDS, Firma Oxford Instruments INCA 300) detektiert, das eben in der Lage ist, Energie und Intensität der Röntgenstrahlen zu bestimmen. Diese Methode erlaubt die quantitative Bestimmung der chemischen Zusammensetzung einer Probe mit einer Genauigkeit von weniger als 1%, während die Detektionsempfindlichkeit bei 0.1 bis 0.01% eines bestimmten Elementes liegt (Mermet and Kellner 2004). Dieser Sachverhalt ist in Tabelle 1 zusammengefasst.

[13] Es sei darauf hingewiesen, dass diese Art der Darstellung eines Atommodells gar nichts mit den tatsächlichen Begebenheiten zu tun hat. Der sonnensystemartige Aufbau dient lediglich zur Veranschaulichung physikalischer Zusammenhänge, die sich jeglicher Anschaulichkeit, wie sie unserer Vorstellungskraft genügen würde, zu entziehen beginnen.

Detektion von	**SE**	**BSE**	**Charakteristischer Röntgenstrahlung/ EDS**
Frage	**Wie?**	**Wo?**	**Was?** und **Wieviel?**
Darstellung von	Oberfläche	Materialkontrast	Qualitative und quantitative Elementanalyse
Auflösung (lokal)	Einige nm Entspricht mehr als 100 000facher Vergrößerung		Einige µm
Genauigkeit/ Empfindlichkeit	—	—	<1% 0,1 – 0,01%

Table 1: Übersicht über detektierte Wechselwirkungen und Art ihres Informationsgehalts.

Die prinzipielle Verwendung eines Elektronenstrahles bedingt eine elektrische Aufladung des Probenmaterials, da ja die Elektronen elektrische Ladung mit sich führen. Werden diese Ladungen vom Probenmaterial nicht abgeleitet, interferieren die aufgestauten Ladungen mit dem Elektronenstrahl und setzen die Qualität der Bilddarstellung drastisch herab. Ist das Probenmaterial elektrisch leitend, werden die Ladungen einfach durch Erdung der Probe abgeleitet. Nichtleitende Proben können mit einer dünnen Gold- oder Kohlenstoffschicht bedampft werden, die wiederum elektrisch leitend ist. Allerdings treten bei diesem Vorgang hohe Temperaturen auf, die das Probenmaterial schädigen können. Weiters kann das Ausgasen einer inhomogenen bzw. feuchten Probe das Hochvakuum, das zur Erzeugung eines stehenden Elektronenstrahls notwendig ist, empfindlich stören und somit die Lebensdauer des REMs herabsetzen. Daher müssen nach wie vor bei herkömmlichen REMs die Proben vorher entgast und getrocknet werden. Ein Vorgang, der bei manchem archäologischen Material fatale Folgen hätte. Eine andere Möglichkeit, die Probe zu entladen besteht in der Verwendung eines atmosphärischen REMs, wie es VIAS zur Verfügung steht.

Bei REMs diesen Typs wird ein Druckgradient durch den Einsatz von Blenden mit Öffnungsdurchmessern von 100 bis 150µm zwischen Probenkammer und Elektronenkanone (Wolframfilament vgl. Figure 3, p.58) erreicht. Während in der elektronenoptischen Säule, also dem Bereich wo der Elektronenstrahl generiert und fokussiert wird, weiter ein Hochvakuum (10^{-6}mbar) besteht, kann der Druck in der Probenkammer von einigen Pascal bis zu 400Pascal, unter Verwendung einer speziellen Blende sogar bis 750Pascal, erhöht werden. Die Entladung der Probe erfolgt nun durch Ionisation der Restgasmoleküle. Zudem ist es nun auch möglich, feuchte und leicht entgasende Proben zu untersuchen. Eine besondere Probenvorbereitung entfällt somit gänzlich. Es ist im Gegenteil sogar möglich, Proben, die besonders empfindlich gegen Hitze und Austrocknung sind (z.B. Textilien), in einer Wasserdampfatmosphäre zu untersuchen. Ein Nachteil von atmosphärischen REMs ist, dass sich die Vergrößerung mit zunehmendem Druck verschlechtert, da der Elektronenstrahl mit dem Restgas wechselwirkt und aufgestreut wird. Allerdings sind die Vergrößerungen, die auch hierbei noch erreicht werden (bis zu 30 000fach) für die meisten archäologischen Fragestellungen völlig ausreichend.

Anwendung in der Archäologie

Ein REM kann in der Archäologie überall dort zum Einsatz kommen, wo die Darstellung und Analyse von Oberflächen von Interesse ist. Zusätzlich lässt sich Information über die chemische Zusammensetzung des Probenmaterials gewinnen. Auch bei dieser Methode ist ein disziplinenübergreifender Ansatz notwendig, da man bestimmte Fragestellungen oft erst mit Hilfe von Experten verschiedener Fachrichtungen formulieren kann. Primär ist aber für den Archäologen von Bedeutung, dass mit einem atmosphärischen REM fast jedes Objekt ohne Vorbehandlung zerstörungsfrei untersucht werden kann. Bei der Bergung eines Objektes sollten auf jeden Fall alle oberflächen- und die chemische Zusammensetzung verändernde Maßnahmen vermieden werden. In der Folge kann eine erste Materialanalyse des Objektes im REM dem Restaurator schon wesentliche Hinweise auf mögliche Restaurationstechniken geben. Generell sollten Proben unverändert zur Untersuchung am REM gelangen. Korrosion, metallurgische Prozesse oder auch restauratorische Maßnahmen sind Einflüsse, die die Oberfläche und Zusammensetzung eines Artefakts verändern können.

Obwohl bei zahlreichen Fragestellungen Vergrößerungen ausreichen würden, wie sie ein Lichtmikroskop auch bietet, ist der Einsatz eines REMs wegen der ausgezeichneten Tiefenschärfe natürlich von Vorteil. So wird die Analyse von Werkzeugspuren oder Schnittspuren wesentlich erleichtert. Im konkreten Fall handelt es sich um einen Handwurzelknochen einer abgetrennten menschlichen Hand. Dieser wurde in einer Grube innerhalb der neolithischen Kreisgrabenanlage von Schletz gefunden, und es stellte sich die Frage, ob die Abtrennung intentionell bzw. mit welchem

Werkzeug sie erfolgt sein könnte. Öffnungswinkel und vor allem die Rillen an den Schnittwänden (Figure 5) scheinen einen sägend geführten Schnitt mit einem Silex zu belegen, der an dieser Stelle der Hand angesetzt wurde, um die Sehnen zu durchtrennen. Die Kombination zweier aus geringfügig verschiedenen Blickwinkeln aufgenommener Bilder gibt zusätzlich die Möglichkeit einer stereogrammetrischen Aufnahme. In Verbindung mit der ebenfalls zur Verfügung stehenden passenden Software (Firma Soft Imaging, Analysis 3.2) können dreidimensionale Modelle erstellt und vermessen werden.

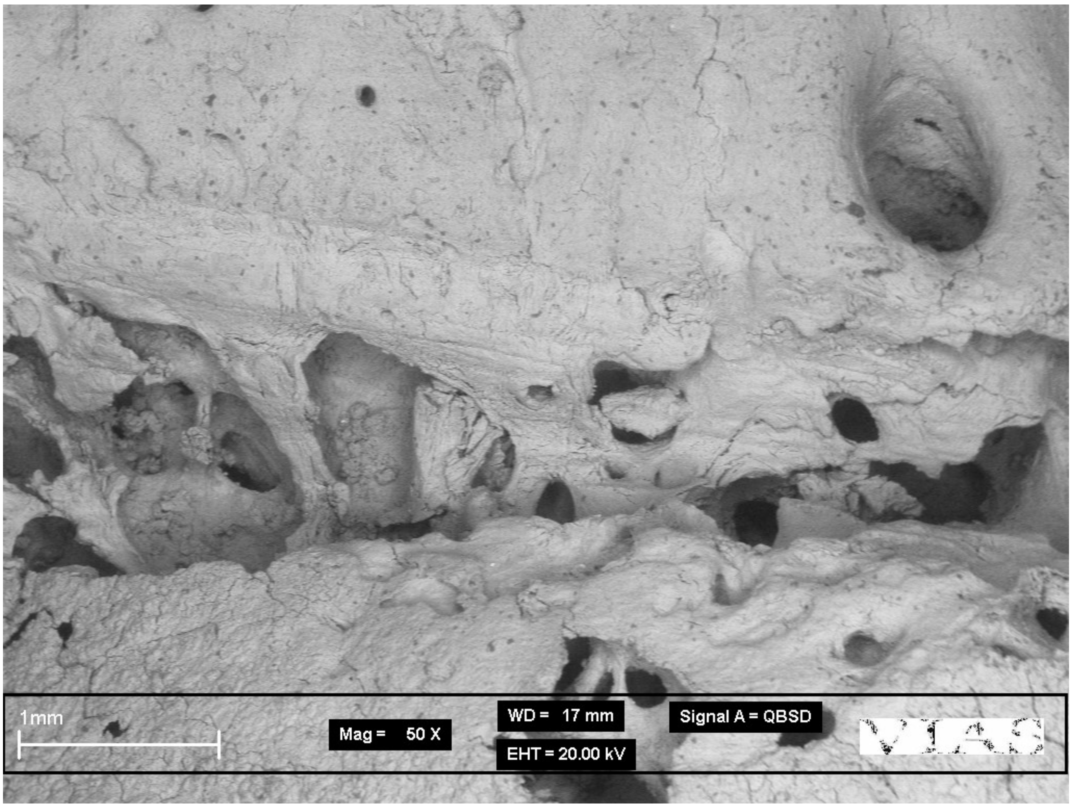

Figure 5: QBSD-Bild (QBSD- four quadrant backscatter detector) des Handwurzelknochens aus der Kreisgrabenanlage Schletz. Die Längsrillen an den Wänden des Schnitts deuten auf einen sägenden Schnitt mit einem Silex hin (Aufnahme: M. Kucera).

Weiters wurden in Zusammenarbeit mit der anthropologischen Abteilung des Naturhistorischen Museums Wien Schnittspuren an Halswirbeln eines männlichen Individuums mit dem REM untersucht. Bei der Freilegung des awarenzeitlichen Gräberfeldes in Mödling/ Goldene Stiege in den Jahren 1967 bis 1973 konnten insgesamt drei Dekapitationsfälle dokumentiert werden, wobei jeweils die Schädel in anatomisch korrekter Lage vorgefunden wurden (Wiltschke-Schrotta and Stadler 2005). Die Verletzungen an der Halswirbelsäule des einen Individuums (Ind. 334) lassen eher auf einen Angriff mit einer messerähnlichen Waffe von vorne schließen, bei dem der Kopf nicht gänzlich abgetrennt wurde. Bei den anderen beiden dürfte es sich allerdings eindeutig um Dekapitationen handeln. Bei genauer Betrachtung des 7. Halswirbels von Ind. 334 in Figure 6, ist die glatte Schnittfläche (in Bildebene) zu erkennen, die keinen Ansatz für einen weiteren Schlag aufweist. Zudem ist die Kante der so geschaffenen Fläche mit der Außenseite des Wirbelkörpers sehr scharf und deutlich zu sehen. Daraus lässt sich schließen, dass der Kopf mit einem einzigen ziehenden Schlag einer scharfen Waffe abgetrennt wurde. Der Schlag wurde von hinten normal auf die Wirbelsäule geführt, was eine geplante Hinrichtung wahrscheinlich macht. Interessant ist in diesem Zusammenhang, dass die Toten ein formelles Begräbnis erhalten haben.

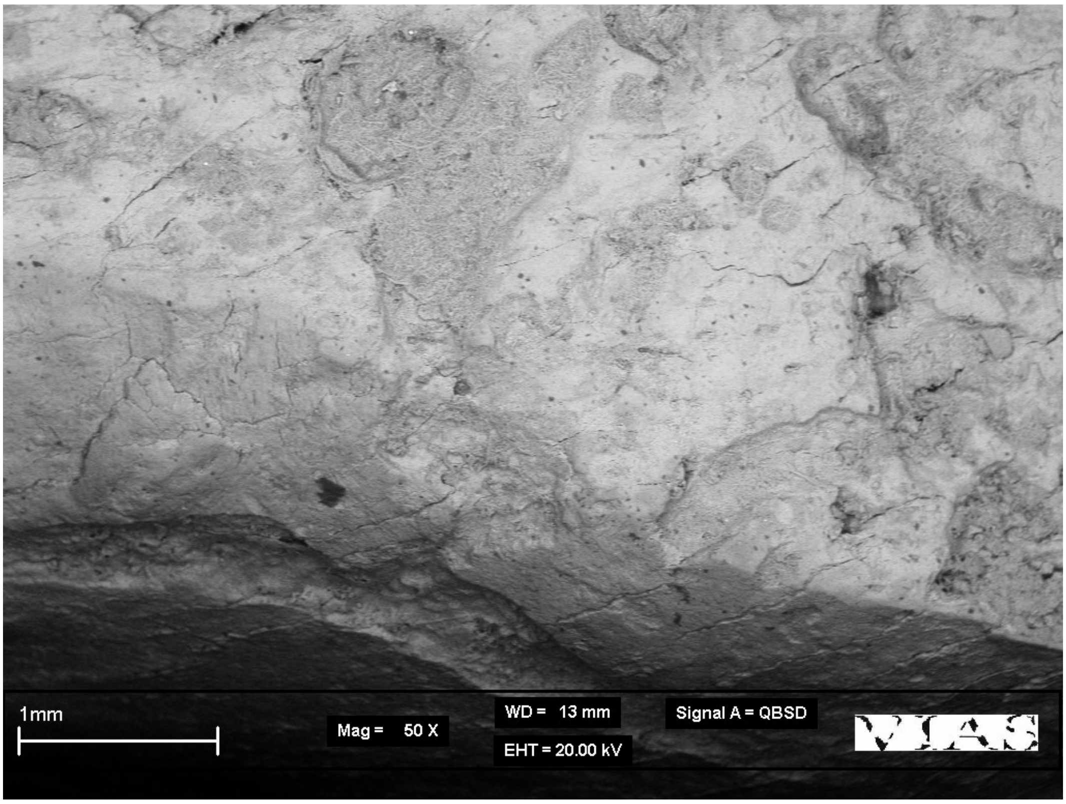

Figure 6: QBSD-Bild des 7. Halswirbels von Ind. 334 (Mödling/ Goldene Stiege). Zu erkennen ist die glatte Schnittfläche in Bildebene und die klare Schnittkante (Aufnahme: M. Kucera).

Bei besonders sensiblen Fundobjekten ist es oft nur möglich einen Abguss, bzw. eine Replik zu analysieren. Gerade paläoanthropologisch bedeutendes Material wird nicht sehr gerne aus der Hand gegeben. Daher sollen in Zusammenarbeit mit dem Institut für Anthropologie der Universität Wien[14] die oberflächendarstellenden Möglichkeiten verschiedener Abgussmaterialien im REM untersucht werden. Anlass hierzu waren in Usbekistan angefertigte Abgüsse von Zähnen eines 8 – 12 Jahre alten Kindes, die zusammen mit Teilen des Schädels 2003 in Obi-Rakhmat/ Usbekistan gefunden wurden. Klingenformen, die dem Mittelpaläolithikum zuzuordnen sind, erlauben eine Altersangabe von 100 000 bis 70 000 Jahren BP (Glantz et al. 2008). Erste Analysen der Abgüsse unterstreichen bereits die

[14] In Zusammenarbeit mit Mag. Bence Viola/ Institut für Anthropologie.

Vorteile dieses Verfahrens. Figure 7 zeigt die SE-Aufnahme eines Backenzahnes (M1). Die Oberfläche des Zahnes erscheint sehr gut reproduziert. Deutlich sind Schlifffacetten zu erkennen. Auch hier sind Tiefenschärfe sowie die Möglichkeit einer dreidimensionalen Darstellung von großer Bedeutung.

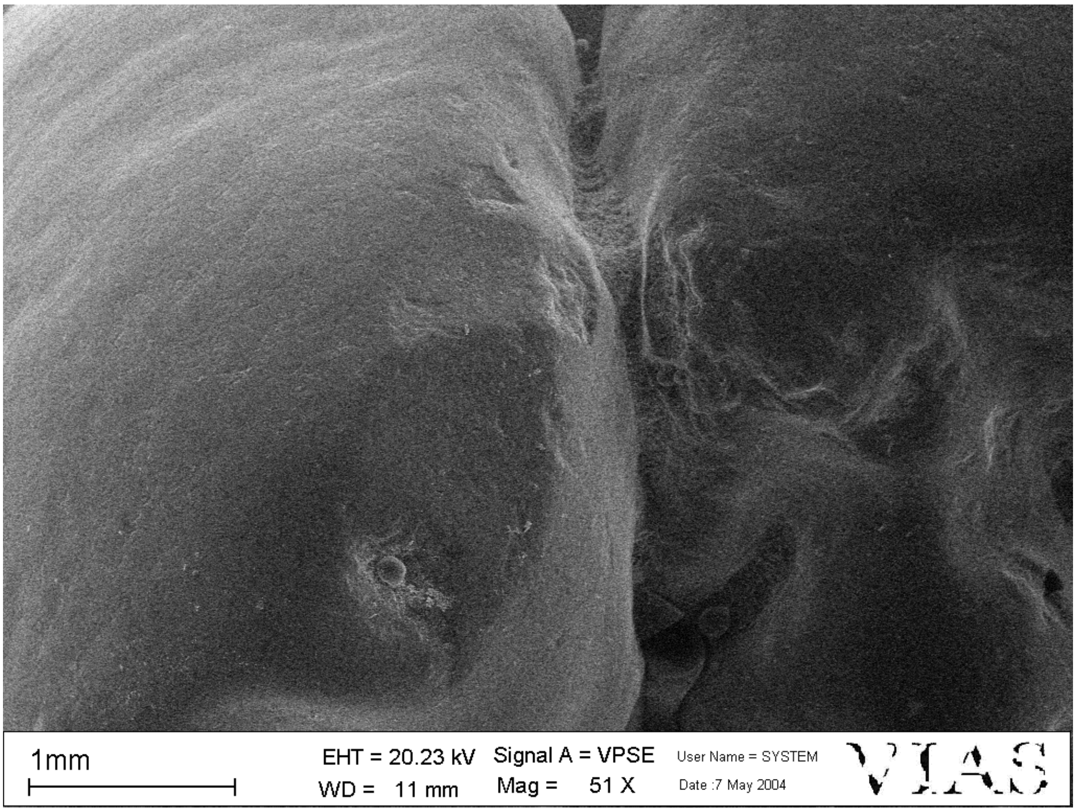

Figure 7: VPSE-Bild (VPSE – variable pressure secondary electron) des Backenzahns (M 1) aus Obi-Rakhmat/ Usbekistan. Schlifffacetten und gute Reproduktion der Zahnoberfläche durch den Abguss (Aufnahme: M. Kucera).

Zu den besonders sensiblen Fundstücken zählen Textilien. Als Beispiel soll die Analyse eines Textilfragmentes aus Mühlbach am Hochkönig / Sbg. angeführt werden. 1968 wurde hier durch Dr. Richard Pittioni ein Aufbereitungsplatz für Kupfererze mit Feuchtbodenbedingungen untersucht. Da kein ^{14}C-Datum vorliegt, lässt sich die Fundstelle bis dato nur archäologisch datieren: eine tordierte geschmiedete Rollennadel, Keramik mit Leistenzier und Feinware mit Kornstich und kleinen, von innen herausgedrückten Buckeln. Analogien lassen sich am Ende der Frühbronzezeit und am Beginn der Hügelgräberbronzezeit ausmachen, je nach Ansatz also das 16. - 15. Jh. v. Chr., nach Meinung des Ausgräbers Dr. Clemens Eibner aber spätestens in Bronzezeit B1. Das vorgestellte Textilfragment (Mitterberg - Fnr. 255 - Abb. 6) ist einer von insgesamt vier geborgenen Textilresten[15]. Von Interesse war einerseits die Bestimmung der verwendeten Tierart, andererseits auch ob es sich um rezentes

[15] Karina Grömer, Clemens Eibner, Mathias Mehofer, Mitterberg – Funde von Geweben aus der Bronzezeit, (Publikation in Vorbereitung).

Gewebe handeln könnte. Das abgebildete Textil wurde komplett in das Rasterelektronenmikroskop eingebracht und im VP - Modus analysiert. Von Vorteil war hierbei die große Probenkammer des Geräts, sodass keine Materialprobe entnommen werden musste. Anhand der Überblicksaufnahmen (Figure 8) kann man feststellen, dass es sich um eine Leinwandbindung handelt. Ebenso ließen die Aufnahmen bei 1300facher Vergrößerung (Figure 9) erkennen, dass es sich bei dem Textil um Schafwolle handelt, die zudem stellenweise schon stark abgebaut ist, sodass es sich nicht um rezentes Gewebe handeln kann.

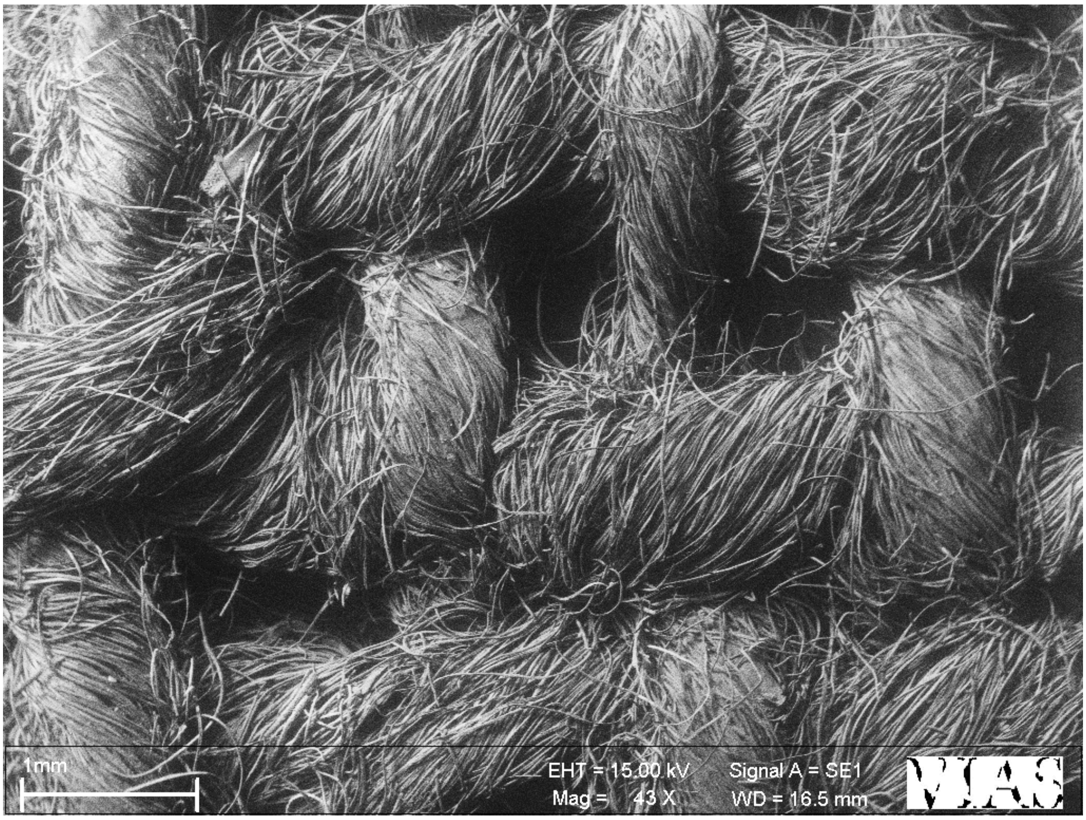

Figure 8: Textil Fnr. 255, die Leinwandbindung lässt sich gut erkennen (Photo: M. Mehofer).

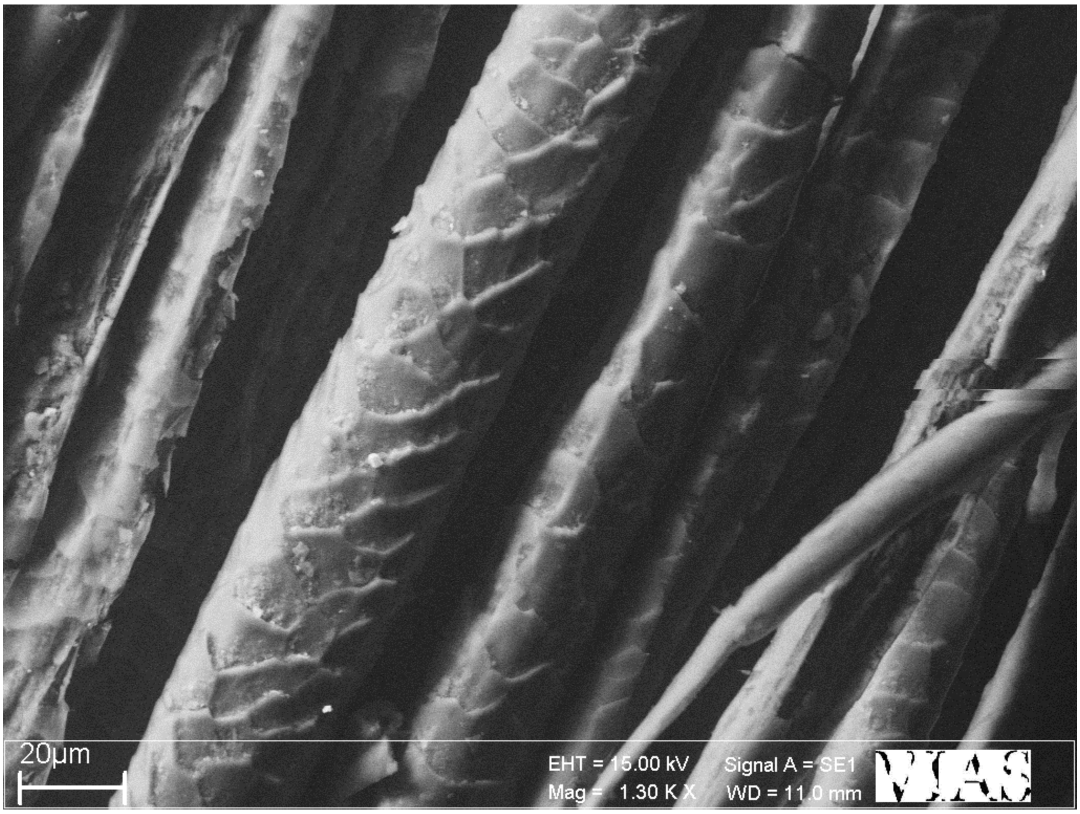

Figure 9: Textil Fnr. 255, Detailaufnahme der Fäden lassen auf Schafwolle als verwendetes Material schließen (Photo: M. Mehofer).

Ein großer Bereich elektronenoptischer Methoden in der Archäologie wird durch die Analyse metallischer Proben abgedeckt. Derlei Untersuchungen setzen detaillierte Kenntnisse metallurgischer Prozesse in ur- und frühgeschichtlicher Zeit voraus. Vor allem die im Vorhinein nicht einschätzbaren Inhomogenitäten archäologischen Probenmaterials stellen ein Problem dar. Die quantitative Analyse beruht im Wesentlichen auf dem Vergleich der tatsächlich detektierten Röntgensignale aus dem Probenmaterial mit einem Materialstandard bekannter Zusammensetzung, die dem Probenmaterial möglichst ähnlich sein sollte (Lyman et al. 1990). Nun ist aber archäologisches Probenmaterial größtenteils durch individuelle Herstellungsprozesse gekennzeichnet und hat somit eine große Varianz im Bereich der Materialhomogenität. Diese Tatsache führt einerseits zu bedingter Einsetzbarkeit von Standards, was wiederum einer exakten Quantifizierung der Messergebnisse entgegenwirken kann. Andererseits bietet sich erst dadurch die Möglichkeit, herstellungsspezifische Phänomene einzelnen werkstatttypischen Gruppen zuzuordnen. Diese Einflussfaktoren (Korrosion und technologische Prozesse) lassen sich sehr gut an den folgenden Untersuchungsergebnissen eines Gürtelbeschlags aus dem landnahmezeitlichen Reitergrab von Gnadendorf zeigen.

Ergänzend zu den bereits im letzten Heft erschienen Beitrag zur Rasterelektronenmikroskopie (Mehofer and Kucera 2005) sollen hier auch noch weitere Untersuchungsergebnisse zur Bestattung eines jungen Mannes vorgestellt werden (Daim and Lauermann 2006). Im Rahmen der Vorbereitung zu einer umfassenden Publikation dieses Befundes wurden auch sämtliche Edelmetallgegenstände hinsichtlich ihrer Herstellungstechnik und chemischen Zusammensetzung analysiert. Ebenso sollte die Materialzusammensetzung der einzelnen Fundgegenstände miteinander verglichen werden. Aus der mehrteiligen Gürtelgarnitur wurde ein wappenförmiger Beschlag Inv.Nr. 19681/17 mit erhabenem floralen Dekor ausgewählt und analysiert. Er wurde auf der linken Beckenschaufel des Bestatteten gefunden. Der aus Silber bestehende Beschlag weist einen erhabenen Rand mit Palettenverzierung (Figure 10) auf, die Zwischenflächen sind vergoldet. Die Befestigung am Gürtel erfolgte durch drei an der Rückseite mitgegossene Nieten. Da er bereits stark fragmentiert war, stellte sich auch hier die Frage nach der Herstellungstechnik des Objektes. Die Messung erbrachte für die vergoldeten Bereiche (Figure 11– Spektrum 1) einen Quecksilberanteil (Table 2) von bis zu 7,1 Gew.%, sodass auf eine Feuervergoldung geschlossen werden kann. Spektrum 2 zeigt die Messergebnisse des Grundmaterials (Silber). Der geringe Anteil an Gold könnte Reste der Vergoldung darstellen, die versehentlich auch in diesem Bereich durchgeführt wurde.

Figure 10: Gnadendorf – Gürtelbeschlag Inv.Nr. 19681/17 (Photo: M. Kucera).

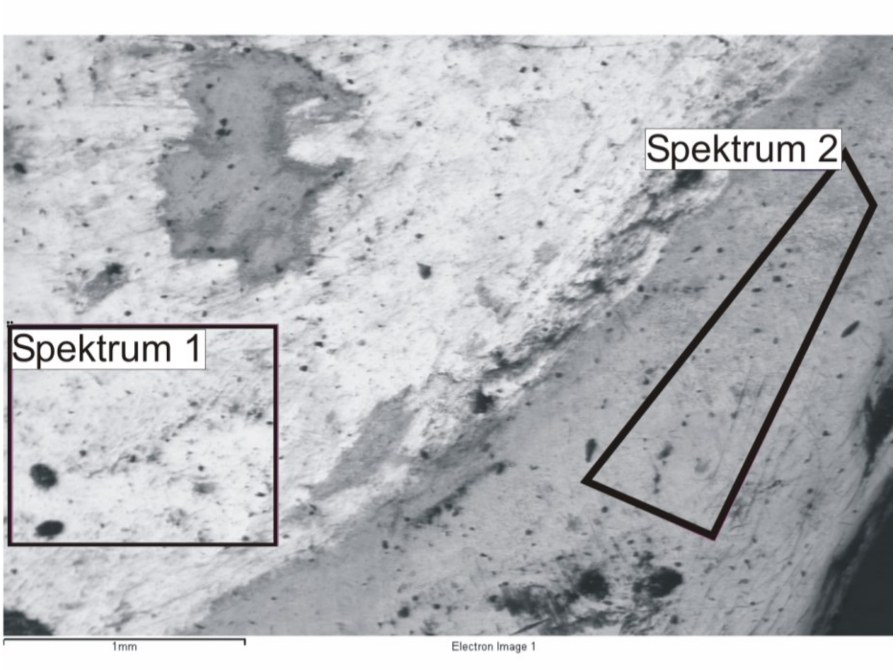

Figure 11: Gürtelbeschlag Inv.Nr. 19681/17, QBSD – Bild des Randbereiches, hellgrau - vergoldete Bereiche, dunkelgrau – Grundmaterial (Silber) (Photo: M. Mehofer).

Bei dieser Oberflächenveredelung wird Goldamalgam (Hammer 1998), eine Mischung der grauen γ - Phase - Au_2Hg mit Quecksilber (Au_2Hg enthält 33% Quecksilber) auf einen Grundwerkstoff aufgetragen und erhitzt. Der optimale Temperaturbereich für den Vergoldungsprozess liegt laut Anheuser zwischen 250-350°C, die Temperatur wird in diesem Bereich für ca. 10 Minuten gehalten, währenddessen geht die γ - Phase in die gelbe ζ - Phase und dann in die α - Phase des Goldamalgams über. Vergoldung auf Kupfer ist etwas problematisch, da sich an der Oberfläche des Kupfers eine Oxidhaut bildet, die den Vorgang sehr erschwert. Um den Prozess zu erleichtern, kann vor dem Aufbringen der Amalgampaste reines Quecksilber, das mit Kochsalz, Alaun und Essigsäure (Anheuser 1999) vermengt ist, auf das Grundmaterial aufgetragen – *„Verquickung"* genannt - und dadurch die Oxidbildung aufgehoben werden.

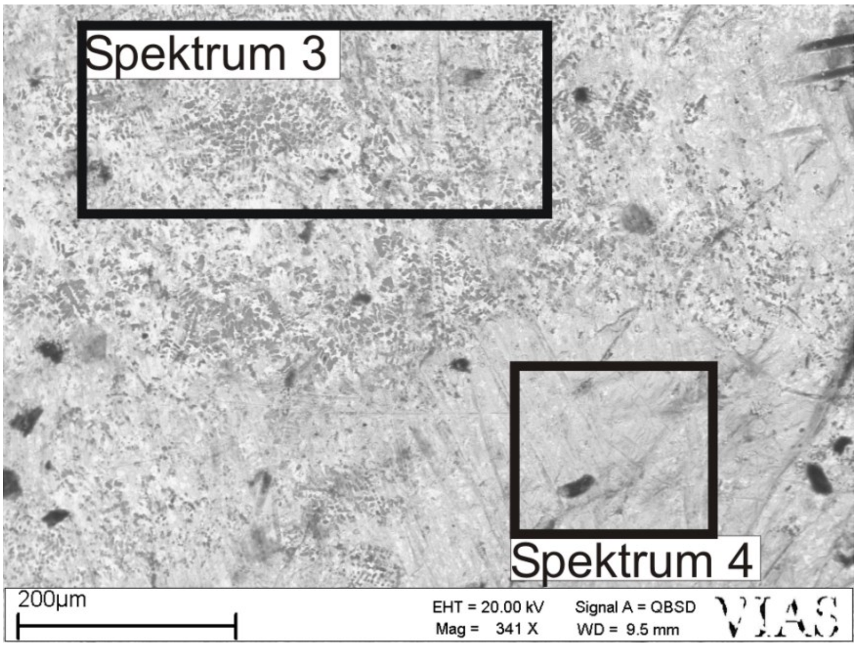

Figure 12: QBSD – Bild, Detailaufnahme des Grundmaterials lässt inhomogenen Elementverteilung im Silber erkennen (Aufnahme: M. Mehofer).

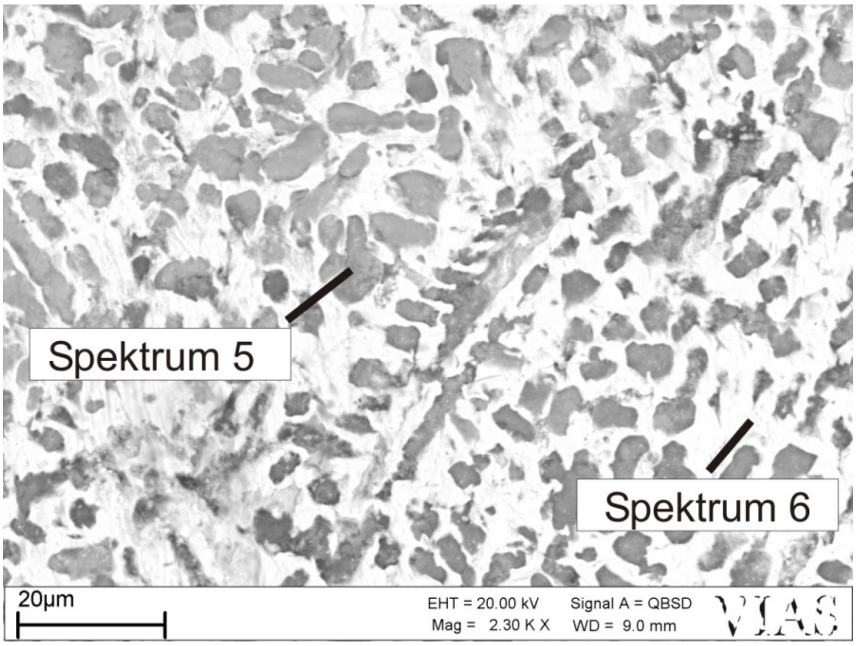

Figure 13: QBSD – Bild, Gussgefüge, in die Silbermatrix (weißgrau) sind Cu – Zn – Pb Entmischungen (dunkelgrau – dendritenförmig angeordnet) eingelagert (Aufnahme: M. Mehofer).

	Cu [%]	σ [%]	Zn [%]	σ [%]	Ag [%]	σ [%]	Au [%]	σ [%]	Hg [%]	σ [%]	Pb [%]	σ [%]	Total [%]
Spektrum 1	7.9	0.7	0		13.4	1.0	71.6	1.9	7.1	2.0	0.00	0	100.00
Spektrum 2	5.9	0.3	1.7	0.3	86.9	0.7	1.1	0.4	0		4.5	0.5	100.00
Spektrum 3	13.2	0.6	2.4	0.5	80.2	1.1	0.0	0	0	0	4.1	0.9	100.00
Spektrum 4	2.3	0.2	0.7	0.2	93.1	0.7	1.1	0.4	0	0	2.9	0.5	100.00
Spektrum 5	82.9	0.5	1.5	0.3	13.6	0.3	0.00	0	0	0	1.9	0.4	100.00
Spektrum 6	9.0	0.2	2.1	0.2	87.3	0.4	0.00	0	0	0	1.6	0.3	100.00

Table 2: Beschlag 19681 / 17: Eregbnisse der EDX-Analyse in Gew.-% , alle Ergebnisse auf 100% normalisiert.

Die Messungen mittels EDS–System ließen des Weiteren innerhalb des Grundmaterials starke Inhomogenitäten in der Elementverteilung (Figure 12, Table 2: Spektrum 3 und 4) erkennen. Einerseits ist der Cu-Gehalt (13,2Gew.%) in Spektrum 3 höher, andererseits kann in Spektrum 4 ein niedriger Cu-Gehalt (2,2Gew.%) sowie ein geringer Au-Gehalt (1,1Gew.%)[16] festgestellt werden. Natürlich muss an der Oberfläche, durch die Bodenlagerung bedingt, immer mit einer Abreicherung von Kupfer gerechnet werden. Allerdings sollte die Beeinträchtigung der ursprünglichen Elementzusammensetzung des Probenmaterials bei nahe beieinander liegenden Messbereichen annähernd gleich bleiben. Eine detaillierte Untersuchung des Messbereichs von Spektrum 3 (Figure 13) ließ erkennen, dass hier ein Gussgefüge (Dendritenstruktur) vorliegt. Das QBSD-Bild zeigt, dass in eine Silbermatrix (Table 2, Spektrum 6) Cu–Zn–Pb-Entmischungen (Table 2, Spektrum 5) eingebettet sind. Bei Betrachtung des bei hoher Vergrößerung aufgenommenen Spektrums 4 konnte festgestellt werden, dass diese Entmischungen fehlen, bzw. die Oberfläche verdichtet erscheint.

Es lässt sich folgender Produktionsvorgang rekonstruieren: Nach dem Guss des Beschlages mit einer Cu-Zn-hältigen Silberlegierung[17], wurde dieser überarbeitet und dessen Oberfläche vor dem Vergolden möglicherweise durch „Weißsieden“ veredelt. Bei diesem Verfahren wird ein Silbergegenstand in eine säurehältige Flüssigkeit getaucht und dadurch das an der Oberfläche vorhandene Kupfer herausgelöst (abgereichert). Dadurch entsteht eine dünne Randschicht, die nur wenig Kupfer enthält und so das Objekt silberreicher erscheinen lässt, als es in Wirklichkeit ist.

[16] Dies wurde an einigen anderen Fundgegenständen festgestellt.
[17] Hier ist an die Verwendung von Altmetall zum Strecken des Silbers zu denken, allerdings wäre auch die Verwendung eines silberhaltigen Kupfererzes denkbar.

Abschließend könnte die Oberfläche vor der Feuervergoldung poliert worden sein, was ihr Erscheinungsbild in Figure 12 (am rechten unteren Rand des Bildes) erklären würde.

Eine immer wiederkehrende Fragestellung bezieht sich auf die Elementverteilung innerhalb einer Probe. Es ist nun möglich einzelne Punkte und Flächen auf der Probenoberfläche[18] hinsichtlich ihrer Zusammensetzung durch Detektion der angeregten charakteristischen Röntgenstrahlung zu analysieren. Zusätzlich bietet das verwendete EDS-System die Möglichkeit, die Verteilung eines oder mehrerer Elemente in einem ausgesuchten Bereich graphisch darzustellen. Bei einem so genannten Mapping rastert der Elektronenstrahl die Probe in wählbaren Schrittweiten ab. Die Signale aus jedem dieser Sektoren werden nun nach Energien getrennt, die wiederum Elementen zugeordnet werden. Gemäß der Intensität der Röntgenstrahlung im Einzelnen werden nun diese Sektoren für jedes Element in verschiedenen Helligkeitsstufen dargestellt. Das Resultat sind „Verteilungskarten" der Elemente. Diese Methode fand unter anderem Anwendung bei der im Rahmen einer Proseminararbeit[19] durchgeführten Untersuchung einer merowingerzeitlichen Gürtelschnalle (Figure 14) aus Sinzing. Bei Schräglicht waren bichrome Tauschierungsarbeiten an der bereits stark korrodierten eisernen Schnalle zu erkennen. Um festzustellen, welche Metalle zur Tauschierung verwendet wurden und ob sich Reste dieser Verzierung auch dort, wo sie visuell nicht mehr vorhanden waren, nachweisen lassen, wurde an diesem Objekt zusätzlich zu den routinemäßigen Einzelanalysen auch ein Mapping (Figure 15) durchgeführt. Um einen möglichst großen Ausschnitt der ungefähr 3cm langen und 2cm breiten Probe analysieren zu können wurde eine minimale Vergrößerung gewählt. Die Probe wurde im Zuge der Restauration mit einem nicht leitenden Schutzfilm umgeben, was im Laufe der Messung immer wieder zu Aufladungen führte, die zum Teil die Bildqualität am Rand der Messfläche beeinträchtigten. Figure 15 belegt anschaulich die Verwendung von Silber und Messing (Kupfer und Zink) als Tauschierungsmaterial.

[18] Es ist zu bedenken, dass auch Atome in oberflächennahen Schichten zu charakteristischer Röntgenstrahlung angeregt werden. Unter Umständen können also Elemente im Inneren der Probe detektiert werden, die auf der Oberfläche gar nicht vorhanden sind.
[19]Durchgeführt von René Mittermann.

Figure 14: Merowingerzeitliche Gürtelschnalle aus Sinzing/ Oberösterreich (2cm breit, 3cm hoch) (Photo: M. Kucera).

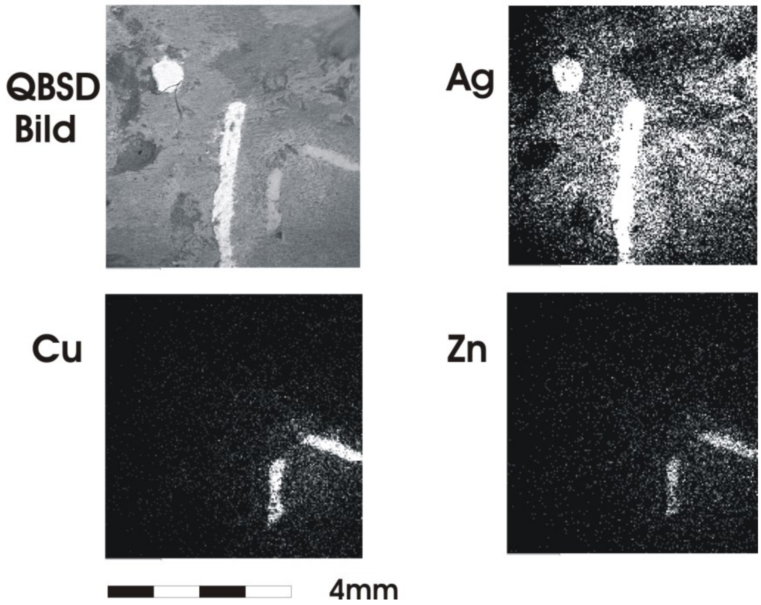

Figure 15: Links oben ist das QBSD-Bild zu sehen. Die anderen Aufnahmen zeigen die jeweiligen Elementverteilungen in diesem Bereich (Graphik und Aufnahmen: M. Kucera).

Zusammenfassung

Die angeführten Anwendungsbeispiele veranschaulichen die vielfältige Einsetzbarkeit eines atmosphärischen Rasterelektronenmikroskops in der Archäologie. Oberflächendarstellungen mit bemerkenswerter Tiefenschärfe sind bis zu mehr als 100 000facher Vergrößerung möglich. Zusätzlich können auch Elementverteilungen sichtbar gemacht werden und die chemische Zusammensetzung einer Probe mit einer Nachweisgrenze von 0.1 bis 0.01% und einer Genauigkeit von unter 1% festgestellt werden. Die Probenauswahl unterliegt nur geringfügigsten Beschränkungen. So können metallische Proben, aber auch nicht leitende, anorganische und organische Proben und sogar feuchte und leicht entgasende Objekte mit einer Länge von bis zu 55cm und einer Höhe von 10 bzw. 20cm zerstörungsfrei und materialschonend untersucht werden. Besonders sensible Materialien wie Textilien können zudem noch in einer Wasserdampfatmosphäre analysiert werden um die Objekte vor Austrocknung zu schützen. Bei der Probenbergung bzw. Probenentnahme sind alle Maßnahmen zu vermeiden, die in irgendeiner Art die Oberfläche und die chemische Zusammensetzung des Objekts verändern oder die bestehende elektrische Leitfähigkeit herabsetzen könnten. Die Rasterelektronenmikroskopie reiht sich somit in den immer größer werdenden Kanon naturwissenschaftlicher Methoden in der Archäologie ein, deren gezielte Anwendung in disziplinenübergreifender Zusammenarbeit wertvolle Beiträge zur Beantwortung archäologischer Fragestellungen liefern können.

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PAPER #2: Efficient but destructive: A test of the Dental Wash technique using Secondary Electron Microscopy

Preamble

Most material analysis is at least minor invasive, which demands the controlled destruction of parts of archaeological material. For this purpose routines and suggestions for possible results are desirable to be available in advance. For the analysis of biofacts embedded in dental calculus teeth can be treated with dental wash technique. The amount of damage caused by this method on the surface of the examined teeth is discussed within this paper. Best practice and application workflows but also limits of dental wash technique are argued and defined.

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keywords: microfossil, microwear, paleodiet, shellmound, dental calculus, Secondary Electron Microscope.

Abstract

The Boyadjian et al dental wash technique provides, in certain contexts, the only chance to analyze and quantify the use of plants by past populations and is therefore an important milestone for the reconstruction of paleodiet. With this paper we present recent investigations and results upon the influence of this method on teeth. A series of six teeth from a three thousand years old Brazilian shellmound (Jabuticabeira II) was examined before and after dental wash. The main focus was documenting the alteration of the surfaces and microstructures. The status of all teeth were documented using macrophotography, optical light microscopy, and atmospheric Secondary Electron Microscopy (aSEM) prior and after applying the dental wash technique. The comparison of pictures

taken before and after dental wash showed the different degrees of variation and damage done to the teeth but, also, provided additional information about microstructures, which have not been visible before. Consequently we suggest that dental wash should only be carried out, if absolutely necessary, after dental pathology, dental morphology and microwear studies have been accomplished.

Introduction

The combination of microwear analysis with plant microfossil analysis is particularly valuable when assessing causes of dental pathology (Fox et al. 1996; Nelson 1997; Reinhard and Danielson 2005; Reinhard et al. 2001). The analysis of dental calculus provides an opportunity to compare plant microfossils (from plants chewed as food, as medicine or even related to the use of the teeth as tools for plant processing) and dental pathology data from the same teeth. Boyadjian et al. (Boyadjian et al. 2007) presented a method of dental wash with a cautionary note regarding apparent damage to the teeth from exposure to processing solution. However, the details of this apparent alteration were not explored. We are taking this opportunity to document the surface alteration of teeth processed with this method.

The dental wash method was developed for specific archaeological conditions. These are archaeological contexts where only very faint residues of dental calculus remain attached to the teeth. In Brazil, these remains are also associated with archaeological contexts where macro remains of plants are poorly preserved. Unfortunately this is common in the tropics (Boyadjian et al. 2007; Piperno and Holst 1998; Scheel-Ybert et al. 2006; Wesolowski 2007; Boyadjian et al. 2006). The dental wash method was developed specifically for these regions to gain essential archaeobotanical data. These are particularly important data for sites for which trace amounts of calculus might be the only source of direct information about the use of plants by past populations.

The dental wash method (Boyadjian et al. 2007), recently reported in this journal, consisted of the immersion of those kind of teeth into a 4% hydrochloric acid solution for 5 minutes. The acid dissolved the dental calculus releasing microfossils. The microfossils were then concentrated in a solution that was used for the preparation of slides, which were examined under light optical microscopy.

Although being efficient for the recovery of microfossils, we noted that this new method resulted in alterations of coloration and surface appearance of the teeth. While this possibly was due to the use of hydrochloric acid, it was not clear to which degree dental wash would hamper or impede microwear and morphological analyses.

The aim of the present paper is to determine the types of alterations found in teeth processed with dental wash. Specifically, we are interested in the state of preservation of micromorphology and microstructure of teeth submitted to dental wash using hydrochloric acid. Finally, we assessed whether posterior treatment with a solution of bicarbonate ($NaHCO_3$) could be efficient in protecting the teeth against the corrosive action of the acidic solution. We systematically scanned six teeth with a Secondary Electron Microscope (SEM) prior and after the procedure and compared the results, focusing on changes in the overall condition of each tooth, its striation pattern and pit sizes.

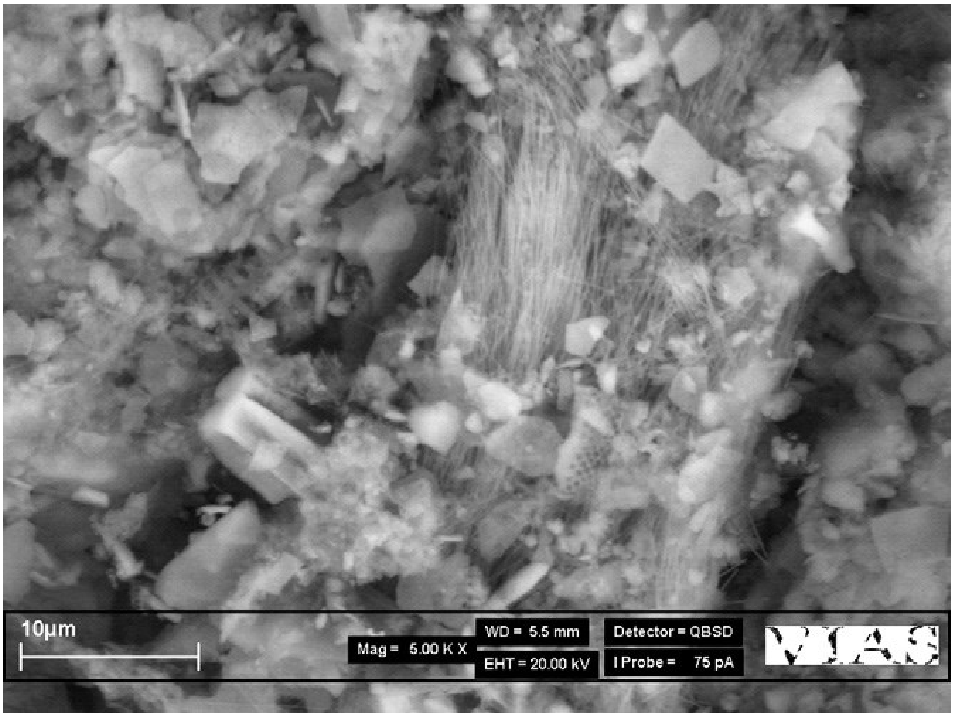


Figure 16: Image obtained with the aSEM of the surface of tooth T3, showing microfossils encrusted in the matrix of the dental calculus (© VIAS, M.Kucera).

Material and Methods

Six teeth from four individuals excavated from the coastal shellmound Jabuticabeira II (Southeast Brazil) were selected. Teeth of this site were chosen due to three main reasons. First, the state of preservation of the teeth of this collection varies substantially, rendering the comparison of them especially informative. Second, in this collection dental wear is usually severe in adults and slight in children, so the effect of dental wash can be observed not only in teeth with distinct attrition degrees, but also in enamel and secondary dentin (mainly in adults). Finally, because this group subsisted mainly on marine resources (Klökler 2003; Richards et al. 2007) sand and other abrasives produced microwear, an important marker for dietary reconstruction. In addition the phytoliths from plants chewed or processed with the teeth are also believed to promote dental attrition or abrasion (Ciochon et al. 1990; Danielson and Reinhard 1998; Nelson 1997; Walker et al. 1978).

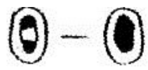
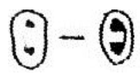
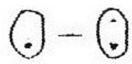
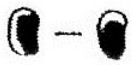
Since this is a paper on methodology, we present a summary of the most important data on the Jabuticabeira II shellmound in Table 3. The teeth selected for the evaluation of the effects of dental wash are listed inTable 4. These teeth, all containing only faint deposits of dental calculus, represent five well preserved samples (one juvenile tooth and four adult teeth) and one poorly preserved, friable adult tooth. Among the well preserved teeth, we chose samples with distinct degrees of dental wear, varying from score 1 to 7 following Brothwell (Brothwell 1981).

All selected teeth were photographed, documented and analyzed with an atmospheric Secondary Electron Microscope (aSEM) before and after dental wash. While the macro-pictures were taken at the University of São Paulo (Brazil), those using the aSEM were carried out at the Vienna Institute for Archaeological Science (VIAS) at the University of Vienna (Austria).

The setup of this aSEM (LEO EVO 60 VP, now Zeiss) is specialized to analyze most of archaeological samples, because it is non-destructive and has an unusual size of the specimen chamber (40cm in diameter). The discharge is solved with traditional SEMs in covering the sample with carbon or gold, which might have some negative effects, due to the high temperature applied during this process. A gold- or carbon- covered surface might also influence following treatments and investigations. In contrast, atmospheric SEMs work at low vacuum (within the range of 10 to 400 Pascal) inside the specimen chamber and therefore solve the discharge of the sample by ionizing the residual gas. The electrons, which are used to analyze the surfaces of the samples, induce the charge of the specimen. Additionally, since the samples are not exposed to high vacuum (which sometimes can alter them as well, especially if the sample is not homogenous, is porous and/or contains air inclusions), this atmospheric SEM is indeed very gentle to archaeological remains. Thus, in using atmospheric SEMs the analyzed surfaces represent the natural state of the samples (compare previous article Kucera and Mehofer, 2005).

Location	Southern Brazil; Santa Catarina State - Jaguaruna region (28º36´S e 48º57´W).
Dimensions	Length: 400m; width: 200m; height: 6m (DeBlasis et al. 1998).
Datation	Dozens of dates were obtained. They indicate a period of continuous occupation of more than 1000 years between 2890 +/- 55 and 1805+/- 65 yBP (1σ, uncalibrated) (DeBlasis et al. 2007).
Estimated number of skeletons	More than 43,000 (Fish et al. 2000).
Burial offerings	Hearths, pebbles, postholes, faunal remains (mainly fish, but there are also marine and terrestrial mammals and birds) (Klökler and Figuti 2001). Some lithic artifacts related to plant processing like mortars, were also found (Scheel-Ybert et al. 2006).
Sediment types	Repetitive deposition of shells layers (underneath and above the corpses), intercalated by lenses of different colored soil. The most recent layers of the site are composed mainly by “black earth” (dark soil rich in organic matter) while the oldest ones are mainly shell and sand layers (Barbosa 2007).
Function	The great number and density of burials, the postholes surrounding them and the absence of evidence of habitation suggest this site was the outcome of repeated funerary rituals (Fish et al. 2000; DeBlasis et al. 1998; DeBlasis et al. 2007).
Main bioanthropological data	High frequency of infections, more osteoarthritis in upper than in lower limbs, low trauma frequency (accidental or due to violence), low stature (Okumura and Eggers 2005; Storto et al. 1999). Low auditory exostosisfrequency (Okumura et al. 2007). Caries index is almost null and degree of dental wear is high (Storto et al. 1999). People from this site were considered morphologically similar to the individuals buried at nearby sambaqui sites, whether from riverine or coastal shellmounds (Neves and Okumura 2005; Bartolomucci 2006; Eggers 2009).
Main faunal remains found	The mollusk shells are predominant, mainly in the shell layers. But, in the dark soil layers analyzed, there were mainly fish remains (making up 78% to 97% of the faunal remains found). Among the identifiable remains, the most abundant were from catfish (*Ariidae*) followed by croaker (*Micropogonias furnieri*). In the dark layers, remains from mammals, birds, reptiles and mollusks were much less frequent than those of fish. Above the burial, concentration but not variability of faunal remains was higher than in the shell layers (Barbosa 2007).
Main plant remains found	Information about plant remains is scarce. Charcoal (anthracological) analysis revealed that this site was located at the “restinga” forest (Scheel-Ybert et al. 2006), but the Atlantic Rainforest was also part of the site catchment area (Bianchini 2008), a region very rich in plant resources. Seeds, palm fruits, as well as wood from the Lauraceae family seems to be related to funerary rituals (Bianchini 2008). Phytoliths and starch grains from dental calculus from the Jabuticabeira II skeletons could not yet be identified. Anthracological analyzes suggest that people from this and other sambaquis “might have managed the landscape, specially regarding Myrtaceae plants, modeling the environment according to rules inherent to their culture ”(Bianchini 2008).
Stable isotope analysis	Carbon and nitrogen values range between -10.01 to -11.17‰ and 16.39 to 17.85‰, respectively, suggesting a diet strongly based on aquatic resources (Richards et al. 2007).

Table 3: Main characteristics of Jabuticabeira II (a Brazilian shellmound or sambaqui) - the source of the teeth analyzed herein.

sample number	burial	individual	age	sex	teeth	preservation	dental wear score (Brothwell, 1981)	chemical treatment
T1	IIIc – L6	1	juvenil	?	1º.r.inf.m.	well preserved	1 	dental wash
T2	XLIII – L1.77	2	middle adult	♂	2º.r.sup.pm.	well preserved	6 	dental wash + $NaHCO_3$
T3	XLI a– L2.05	3	adult	♂	1º.l.inf.pm.	well preserved	5 	dental wash + $NaHCO_3$
T4	XLI a– L2.05	3	adult	♂	2º.r.inf.pm.	well preserved	4 	dental wash
T5	XLIII – L1.77	2	middle adult	♂	2º.r.sup.i.	well preserved	5 	dental wash
T6	CXIV – L6	4	middle adult	♀	pm	very badly preserved	7 	dental wash

r.= right, l.= left; inf.= inferior, sup.= superior; i.=incisor; pm.=pre molar, m.= molar

Table 4: Main characteristics of the samples used for aSEM analysis (teeth were selected from the Jabuticabeira II shellmound, Brazil).

Three different detectors were used during the investigations. Using low currents, the Secondary Electron Detector (indicated as SE in Figure 17) gave sufficient signals for the visualization of the surfaces. For those samples with a high amount of charge, a lower vacuum was necessary to discharge the specimen. Charge varies due to the sample´s specific conductivity, which depends on the micro composition of the samples and polluting sediments on them. In this case the surface is represented throughout the detection of photons resulting from the interaction of secondary electrons with the residual gas detected by the Variable Pressure Secondary Electron Detector (indicated as VPSE Figure 17). Obviously, decreasing the vacuum diminishes resolution because of the deflection of the primary electrons. For example, at the pressure of 30Pa magnifications of up to 30.000x are gained, whereas in the high vacuum mode magnifications above 200.000x are possible.

For the present study magnifications below 30.000x were sufficient to show dental microstructures and even to detect microfossils embedded in the dental calculus (Figure 1). Although the aim herein was to establish the impact of dental wash on dental microwear, it became also obvious that analysis of the surface of the teeth using an aSEM provides the chance of detecting microfossils and to estimate their possible distribution as suggested by Reinhard et al. (Reinhard et al. 2001).

Due to different states of charging habits, because of the different state of the surfaces before and after dental wash, it was not always possible to use the same setup of parameters and detectors. Under those circumstances we want to remark that SE and VPSE detectors show the same topography of the surfaces, meaning that the use of different detectors does not jeopardize the analyses of the images.

The third detector identifies the backscattered electrons showing therefore the distribution of different materials upon the surface (Backscatter Detector, indicated with QBSD). It was used when the difference between calculus, enamel or “dirt” was not clearly visible within the SE- or VPSE-pictures. Because these materials show a different density, they are distinguishable with the QBSD.

Before dental wash, an overall and some detailed macro-pictures were taken from the six teeth selected. Then, each tooth was analyzed under the aSEM twice: before and after the dental wash procedure.

The dental wash procedure consisted of an immersion of each tooth into a beaker with 10-20 ml of an acidic solution with HCL at a 4% concentration for 5 minutes. The tooth was gently swirled and then, a smooth new toothbrush was used to liberate the microfossils (for more details see (Boyadjian et al. 2007). After that, the teeth were rinsed with distilled water. However, two of the teeth selected for this study (T2 and T3) were treated with a solution of bicarbonate ($NaHCO_3$) during a few minutes right after the wash (instead of being washed with distilled water), to test if it was possible to stop and restrict the action of the hydrochloric acid on the teeth’s surface. The teeth were not rinsed after the bicarbonate solution wash; just air-dried.

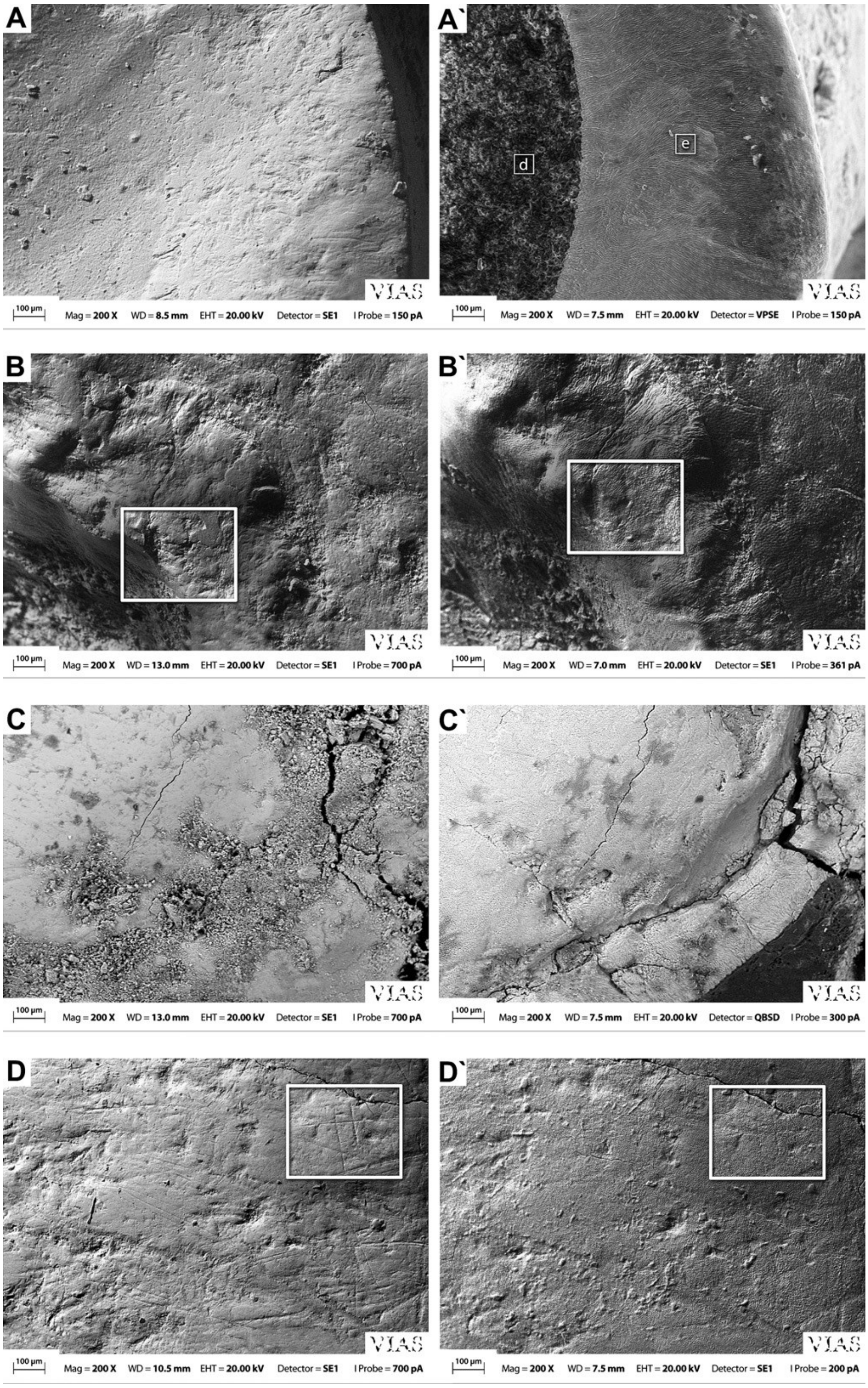


Figure 17: Pairs of images from the surface of the teeth analyzed showing the difference before and after dental wash. A and B, teeth from burial 43; C and D, teeth from burial 41a. A – T2, dental wear degree 6, pre-wash and A'- same area of T2 after dental wash; e=enamel (attention to the prisms) d=dentine; B – T5, dental wear degree 5, pre-wash and B'- same area of T5 after dental wash; C – T3, dental wear degree 5, pre-wash and C'- same area of T3 after dental wash, D – T4, dental wear degree 4, pre-wash and D'- same area of T4 after dental wash.

Before the first scanning, a drawing of the topography of each of the teeth was made. It was important to register the existing micro fractures, fissures and impurities adherent to the tooth surface. Macro pictures were also used to orientate us on the magnified tooth surface in the aSEM chamber and to find exactly the same measured region in the aSEM after applying dental wash. A short written description of the tooth and a documentation of the steps of the procedure were beneficial as well. The scanned line was then marked on each drawing. We tried to focus the measurement line to about the middle of the surface of each tooth. An essential thing to note and remember was the scanning direction, lingual/palatinal to labial/buccal. In the drawing, as well, the indication of the right, left, mesial or distal side of the tooth was made. These remarks were implicitly necessary for each single tooth, because we used different teeth, and we needed to find exactly the same scanned line after the wash.

It was vital to have a continuous picture series of the scanned line of each tooth at the same magnification level. A magnification of 200x proved to be most practical for the investigations of the changes upon the teeth before and after dental wash.

Results

Using teeth with different states of preservation and dental wear prior do dental wash with HCl (with and without posterior buffering with bicarbonate), we obtained distinct results on the changes in the teeth.

Before presenting these data, we want to emphasize that for relocating the scanned line across the teeth after dental wash, the preexisting micro-fissures were very helpful as landmarks. In contrast, the use of patches of impurities was inefficient, since most of the “dirt” as well as the dental calculus remains were removed with the dental wash procedure.

The focus of the analysis was on striation depth, pit size, as well as the overall state of preservation of the teeth. We selected four pairs of pictures (Figure 17) from the 106 pictures taken before and the 71 pictures taken after dental wash. Additionally, two more pictures illustrate the effects caused to teeth with different states of preservation (Figure 18).

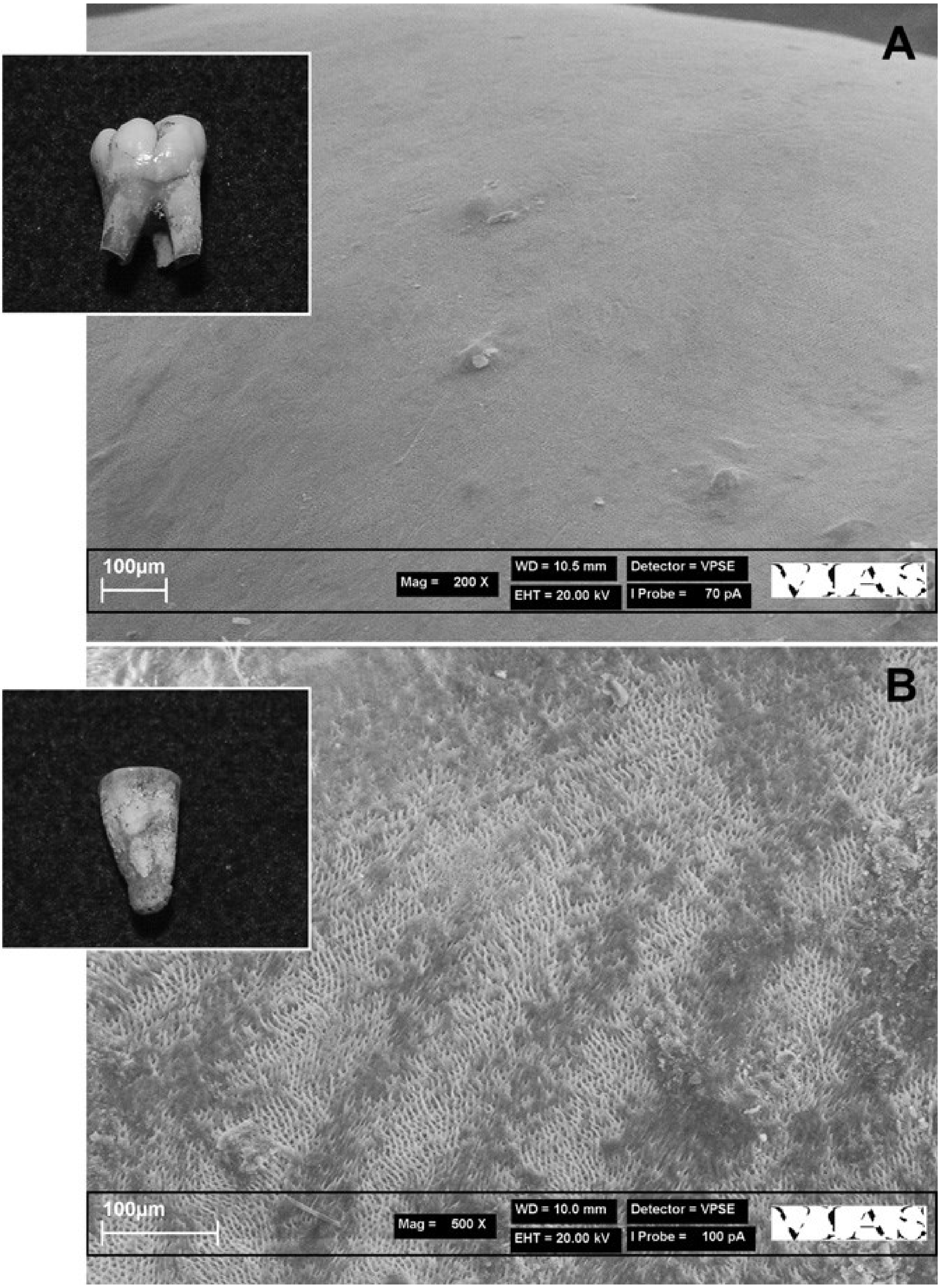


Figure 18: Effects of dental wash when applied to a well preserved tooth (T1) and a badly preserved tooth (T6). **A** – T1: dental wear degree 1, macroscopic picture shows the very well preserved tooth before dental wash and an image from aSEM after dental wash shows the microscopic alterations. **B** – T6: dental wear degree 7, macroscopic picture shows the badly preserved tooth before dental wash and an image from aSEM after dental wash shows the microscopic alterations.

Figure 19: Image of T6 damaged after dental wash. The arrow points to a region where enamel pieces were detached from the tooth just with a slight impact after the procedure.

In general - as already mentioned before (Boyadjian et al, 2007) (Boyadjian et al. 2007) - all teeth turned opaque and lost their shine macroscopically (see Figure 5 from (Boyadjian et al. 2007). The type of microscopic changes we can best notice among all of the pictures taken refers to Figure 2 A and A'. We observed that after dental wash 100% of the area shown in the picture reveals the ultrastructure of enamel and dentin. The most superficial layer of the tooth was removed and it is possible to clearly distinguish the prisms (that make up the enamel), from the tubules (that constitute the dentin). Besides that, small residue patches and almost all of the micro enamel groves completely disappeared.

However, it was noteworthy that the removal of the superficial dental layers did not always lead to clear exposure of dentin and enamel ultrastructure. This is the case of Figure 2B and B'. Indeed, comparing these pictures we noticed that seven among ten more conspicuous groves (such as the one depicted in the square) were shallower after dental wash.

Another type of alteration concerned the “cleaning” of the tooth (Figure 17 C and C'). In this case, strongly adhered dental calculus and/or “dirt” was removed from very little dental groves, eventually exposing fissures. At the same time, already existing fissures seamed to increase in depth and width. Comparing Figure 2C and C' we observe that the very faint fissures on the left side of each picture became clearer after dental wash. Additionally, on the right side of the pictures the most evident fissure became considerably broader. Similar alterations can also be observed in Figure 17 B and B', where two among three fissures became wider and one in three remained unchanged, while a new fissure is evident only after the dental wash procedure.

Dental wash can also lead to a loss in the sharpness and, sometimes, even in the detectability of dental microwear. We noticed this in Figure 17 D', where we identified a smaller number of striations, pits and shallow grooves when compared to Figure 17 D. From the roughly 20 main striations observed prior to dental wash (Figure D), we could only detect six of them after the procedure (Figure 17 D'). The striations that form a double cross in the right superior side of Figure 17 D, almost vanish in Figure 17 D'. However, the horizontal line that exists right below the double cross remains recognizable after dental wash (in Figure 17 D').

When comparing the pictures from the teeth at different states of preservation, we can observe that in T1 (the better preserved tooth), the enamel ultrastructure after dental wash was barely noticeable, while in T6 (the tooth with the worst preservation), the ultrastructure was very clearly apparent after dental wash (as shown in Figure 18). Besides that, the effects of dental wash can be seen macroscopically in T6, since it became even more friable and lost some pieces (Figure 19).

Bicarbonate does not seem to protect the studied teeth against the corrosive effect of hydrochloric acid. To test the effect of bicarbonate applied to the teeth shortly after dental wash, we compared the images taken from T2 (Figure 17 A and A') and T3 (Figure 17 C and C'), teeth that were treated with NaHCO3. In Figure 17 C`, the ultrastructure of dentin and enamel is not as visible as in Figure 17 A'. This discrepancy has to be attributed to a set of factors. Since these two teeth showed different degrees of dental wear, and the most worn tooth is also the one where the ultrastructure turned more visible (T2), we can affirm that bicarbonate has not shown the expected efficiency in protecting the teeth against the corrosive action of the acidic solution. Similarly, when comparing two teeth from different individuals but comparable dental wear, the same conclusion can be drawn. If we compare T3 treated with bicarbonate (Figure 17 C') with T5 that was not treated with bicarbonate (Figure 17 B'), we observe no significant difference regarding the degree of the enamel's microstructure exposition.

Discussion

In our previous study, dental wash was proven to be effective in the recovery of microfossils (Boyadjian et al. 2007). We emphasized that this new method is a very important tool for sites where botanical macro remains are rare and dental calculus is ephemeral (and cannot be detached mechanically with the traditional method).

However, as demonstrated herein, this method must be used with prudence (and only when strictly necessary), because, despite the few minutes of exposure of the teeth to the acidic solution, it can cause several effects. These include an increase in friability of the entire tooth, exposure of enamel and dentin ultrastructure, shallower pits and groves, removal of "dirt" and dental calculus, exposure of new fissures, increase of depth, width and length of already existing fissures, loss of sharpness of striations and pits, and sometimes, even loss of detectability of striations and pits.

The removal of "dirt" and dental calculus through dental wash can be desirable. Obviously, for dietary reconstruction "dirt" should not contaminate the solution. This can be avoided by cleaning the surface of the teeth and the dental calculus very carefully (in order not to take away the faint dental calculus deposits) following the protocol developed by Wesolowski (Wesolowski 2007) and Wesolowski et al. (Wesolowski et al. 2010). Only then one should proceed to dental wash.

In addition, the exposure of enamel and dentin ultrastructure can also be beneficial if one is interested in micromorphology. However, all the other effects of dental wash are detrimental to teeth.

These negative effects can be placed into two major groups of problems: one concerned with the overall preservation of the archaeological record and another one associated with the impairment or increased difficulty for microwear analysis. Tooth preservation is endangered mainly through the greater friability of the teeth, and the enlargement of the preexisting fissures, leading to higher porosity and eventually to greater susceptibility to microorganism attack and accidental breakage. On the other side, greater difficulty in microwear analyses is primarily due to the loss of sharpness of striations and pits.

To try to prevent damage to the teeth we used bicarbonate buffering shortly after dental wash in some of the teeth. However, the effect of NaHCO3 was, if at all, insignificant. Thus, other buffering solutions, or less corrosive dental wash procedures should be tested.

Meanwhile these methods are being developed, we suggest the following recommendations:

- Use dental wash only in sites or individuals with thin dental calculus deposits;

- Choose only loose teeth;

- Among them, select those that have already been analyzed for dental pathology, dental morphology and microwear;

- Make a replica of the tooth (caution must be taken with the further detachment of dental calculus during this process);

- Make photographic records of all the sides of each tooth;

- Use aSEM to analyze the surface of the dental calculus to get a first impression of possible microfossils enclosed in the calculus;

- and finally, proceed to dental wash with moderation and only in cases where there is no other method that can retrieve microfossils.

Conclusion

Although dental wash is a very valuable tool for the recovery of plant microfossils from teeth with faint dental calculus deposits, it can cause considerable damage to the teeth. Some of those effects can even complicate or prevent other kinds of analyses such as dental microwear. Therefore, this method should only be applied when there is no other way of obtaining information about plant use since it is one of the few methods to investigate the use of plants by past populations buried in sites were macro botanical remains are not preserved.

When there is no other option, we also suggest that some preventive actions should be taken before the wash procedure, like recording images of the teeth and doing all possible analyses prior to dental wash (morphological and dental microwear analyses). Instrumentation which is useful for these analyses range from optical light microscopy to atmospheric SEM. Starting with magnifications from 5000x, microfossils become visible within the surface of dental calculus. Thus, the use of an aSEM provides the chance to detect and determine the basic distribution of microfossils randomly visible on the surface of the calculus before dental wash, whereas the use of dental wash is crucial to quantify the complete record and the distribution of microfossils embedded in the dental calculus.

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Portable X-ray fluorescence spectroscopy

PAPER #3: In situ pXRF for archaeological excavations – accuracy vs. soil heterogeneity

Preamble

Soil represents the main component of archaeological material under investigation. Chemical and physical properties of soil determine the results of every archaeological or geophysical investigation. With this paper the huge variety of chemical composition of soil based on anthropogenic and natural processes is presented. Often the natural variety of the chemical and physical properties is outnumbering the possible accuracy and precision of applied techniques. Therefore benefits and limits of applied methods must be argued regarding the respective context. This aspect is also illustrated by the following paper.

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keywords: depositional processes, soil chemistry, portable XRF, Neolithic, Kreisgraben

Abstract

In archaeology, stratigraphic units are characterized by their shape, location, and physical composition. In analyzing these components, archaeological research aims to reconstruct processes of deposition and formation. Interpretations of material analyses are typically biased by this stratigraphic information as revealed through excavation. Nevertheless, it is questionable whether different processes are distinguishable only based on material analysis. In recent years, portable X-Ray Fluorescence (pXRF) systems have been tested for on-site or even in situ measurements of archaeological samples. pXRF has the potential to provide fast and effective monitoring of material characteristics on-site. In this respect, if and to which degree the results represent the archaeological record should be a major concern. The challenge is not to increase precision and accuracy of the used instrumentation, but rather if a qualitative analysis of the relative distribution of different elements

and material properties is possible based on on-site measurements. A possible workflow for recording basic soil parameters during excavation was tested and improved at a Neolithic ring ditch enclosure in Hornsburg, Austria. Based on this work, we suggest a methodology for leveraging the speed and portability of modern pXRF technology to characterize sediments and stratigraphic units in situ. We further propose that the usage of pXRF on-site allows distinguishing different processes by observing basic variations of elements.

1. Introduction

Throughout Austria, Germany, the Czech Republic, Poland, Slovakia and Hungary, comparable monuments of one to five concentric circular ditches, 60 to 200m in diameter with one or more entrances have been documented (Melichar and Neubauer 2010; Trnka 2005). All these monuments – so-called circular ditch systems or Kreisgrabenanlagen (KGA) – date to a very short period from approximately 4900 to 4500 BC, and correspond to the Neolithic Lengyel culture. The general function of these monuments remains unclear, and a great deal of debate circles around ritual purposes. A major factor in the range of possible interpretations is the extensive erosion that partly destroyed most of these monuments. Nevertheless, parts of palisades, pits and single postholes, along with the enormous v-shaped ditches, remain in most cases. The ditches are often still several meters deep and had steeply sloping inner surfaces. The faces have often opening angles below 60°.

One set of questions among many dealing with these sites is the formation processes observed inside the ditches. In many cases, these are truncated due to erosion and show multiple re-cutting and filling episodes. The length of time between reuse episodes and the relative contribution of human and natural infilling are critical components to understand the significance of these monuments within prehistoric communities. Therefore, we have set out to characterize the ditch sediments and stratigraphic layers based on a number of physical and chemical characteristics. This paper presents the application of portable X-ray fluorescence (pXRF) as a method for characterizing the chemical composition of sediments in situ. There has been significant developments in multi-element analyses of archaeological sediments in recent decades, particularly for the analysis of activity zones and the use of space within settlements and houses (Dirix et al. 2013; Fleisher and Sulas 2015; Middleton 2004; Rondelli et al. 2014; Salisbury 2013; Terry et al. 2015; Wells et al. 2007). These analyses are generally done via inductively coupled plasma mass spectrometry (ICP-MS) or optical emission spectroscopy (ICP- OES), wherein samples must be collected, dried, and chemically digested before any determination of elemental composition takes place. Although these methods provide exceptional insights into the patterning of anthropogenic chemical inputs, an obvious downside is that preparation and analyses preclude immediate results during normal a field season. Furthermore, the results can be ambiguous, and interpretations rely on knowledge of underlying geology, digestion methods, and anthropogenic inputs (Dirix et al. 2016; Oonk et al. 2009; Wilson et al. 2009). pXRF seems to provide an alternative method for fast, in-field multi-element characterization, but its application to soil is complicated by the inherent inhomogeneity of soils while still requiring an understanding of local geology. Furthermore, most studies have focused on those elements known to be elevated through anthropogenic activity (e.g., P, Ca, Mg, K). However, one strength of pXRF is that it can measure the total chemical composition of the sample, and therefore sediments can be characterized in terms of elements that are most strongly represented. As our data shows, this can vary considerably.

Although pXRF is not yet a complete alternative to more costly and time-consuming ICP-MS, the method has proved useful as a way to quickly characterize sediments and other geological materials. Bátora et al.(Bátora et al. 2012), for example, used pXRF as one of a suite of non-destructive techniques to examine an Early Bronze Age settlement at Fidvár in Slovakia. Among other results, they identified a pattern of phosphate accumulations outside of houses. Another study from the same site shows good correlation of ICP-OES and pXRF for some elements, but poor results for others, and attributes these to differences between total chemical composition in pXRF and extraction dependence in ICP methods (Gauss et al. 2013).

Several studies demonstrating the reliability of pXRF for archaeological soil samples have not taken advantage of the full portability of the device for in situ measurements, but instead have used it as a portable benchtop unit with prepared samples (Abrahams et al. 2010; Gauss et al. 2013; Lubos et al. 2016). A setup like this is of great use, particularly when other instrumentation is not available, but does not reflect the advantages of in situ measurements. While this application is more portable and less resource intensive than traditional ICP-MS/OES approaches, our goal was to achieve truly in situ measurements, and develop an archaeological chemostratigraphy (Davis et al. 2012; Smejda et al. 2017). We set out to determine (1) which elements can most usefully be measured via in situ pXRF; (2) which are appropriate to characterize sediment layers in anthropogenic contexts; and (3) the optimal workflow for defining stratigraphic units and documenting archaeological data while it is being destroyed.

2. Material and methods

2.1 Site description

In the area around Hornsburg, about 30 kilometers north of Vienna, Austria, two KGA monuments and a related settlement area have been detected and archaeologically examined over the past several decades (Trnka 1991; Kucera 2013; Melichar and Neubauer 2010). Based on the on extensive geophysical and remote sensing data, plus the results of earlier excavations, an entrance area of one of the monuments (site Hornsburg 1) was excavated in 2013-2014. Hornsburg 1 consists of three ditches, two entrances and a concentric palisade in the central place (Figure 20). The monument is situated within a slight depression on the top of a ridge. This secured an exceptionally good state of preservation, as documented during the excavation. It appears that a chromic B-horizon from the original soilscape has been preserved within the depression. Bedrock in this area is covered by deep loess deposited during the most recent ice age.

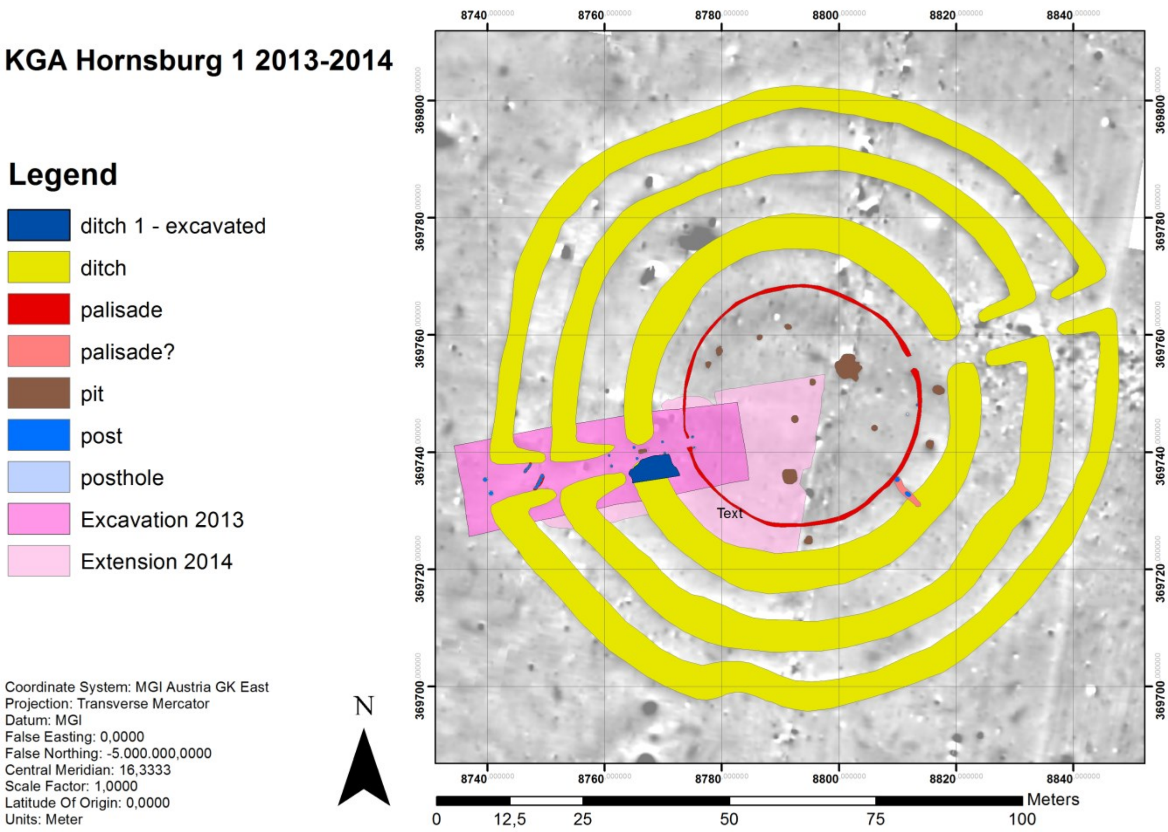

Figure 20: Middle Neolithic Kreisgrabenanlage (KGA) of Hornsburg 1 and location of excavation trenches (© LBI ArchPro, M.Kucera).

2.2 Determination of soil elemental composition

2.2.1 General aspects of pXRF application

Portable, hand-held x-ray fluorescence (pXRF) analyzers provide fast and relatively inexpensive soil chemistry data, and are increasing used in archaeological settings (Ashkanani and Tykot 2013; Golitko 2011; Shackley 2011; Smejda et al. 2017; Tykot et al. 2013). Instruments measure total or near total concentrations of elements and components in a sample over a surface area of less than one square centimeter to a depth of approximately 2 to 4 mm, and display chemical concentration in parts per million (ppm). Whereas XRF has been used successfully in archaeological sciences in recent decades, pXRF enables the examination of materials in situ and in remote areas. Although pXRF instruments could be also set up in lab situation (vacuum, fixed geometrical setting of instrumentation and specimen), settings change and results might be not replicable compared to desktop XRF (Goodale et al. 2012). Differences have been widely discussed (Craig et al. 2007, 2007), and efforts have been undertaken to extend the accuracy and precision limits of pXRF, again mostly for lab-based observations (Johnson 2014). The advantage of pXRF is that by measuring the total chemical composition, including the contribution of the soil parent material in situ, an on-site analysis of archaeological material is provided. Optimally, results are expected to be both replicable and reliable, but the end goal for archaeology are valid and verifiable results (Frahm 2013). However, studies cited above (Frahm et al. 2016; Hunt and Speakman 2015) demonstrate that different parameters lead to different results. Interfering parameters include differences of principle setup of instruments, seasonal and daily changes to soil matrix (e.g. humidity), and geometry of instrument placement (tilt, angle) on a specimen. All these parameters must be accounted for and documented to guarantee reproducibility of results (Goodale et al. 2012). This is an impracticable procedure in typical field conditions, but as we demonstrate, useful results can be achieved nonetheless.

Another even more challenging limiting factor is the heterogeneity of deposits. In addition to interference parameters outlined above, at least two other sedimentary characteristics can limit the reliability of pXRF: grain size variations (Weltje and Tjallingii 2008) and organic matter content (Löwemark et al. 2011). Heterogeneity in both of these might be related to human activity in archaeological settings. Finally, whereas artifacts and soil samples could be measured many times with different methods, an in situ measurement can only be done once under the exact same conditions. For the reliability of the results, accurate documentation and a well-defined survey strategy are crucial.

2.2.2 Description of pXRF instrument and method

A Bruker Tracer IV with a 10 mm^2 XFlash® solid-state silicon drift detector (SDD) and a Rh target x-ray tube operating at 30 µA to 55 µA and 40 kV to 15 kV respectively, was used to measure soil chemical components at specified locations (for general overview of pXRF for environmental samples, including soil, (McComb et al. 2014). A penetration depth of 2 to 4 mm (maximum) for silicates is typical at these energies. The collimator limits the x-ray beam to 3 by 4 mm resulting in a spot size for analysis of approx. 35 mm^2. The system provides a typical resolution of 145 eV at Mn $K\alpha_1$ with an expectable count rate greater than 180,000 cps. Dependent on the excitation energy and measuring time, the detection of light and heavy elements could be optimized for a given situation. Although the system should ideally operate within vacuum and with a specimen holder, it has been designed for the *in situ* use on different materials. For this purpose, different filters can be applied in front of the collector. To increase accuracy for *in situ* measurements, a tripod for holding the instrument stable in front of a specimen is also ideal. Nevertheless, daily routines in the field demand free and handheld positioning. The mass of 2.04 kg (including battery and PDA) and geometric design supports operability under these circumstances.

2.2.3. Data Acquisition

After excavation, the cross section of Hornsburg ditch 1 was recorded with RGB photography. The surface was recorded with a terrestrial laser scanner (VZ400 Riegl LMS) and applying Image Based Modelling. Based on IBM for every photographic sensor a vertical orthophoto of the cross section was generated (Figure 21). During the whole excavation, the ditch was protected by a tent to reduce weathering of sediments. For easier accessibility, boards were placed horizontally in front of the cross section (Figure 22). These facilitated the pXRF measurements by supporting the operator and the stability of the instrumentation. The measurements were undertaken on a cloudy but dry day with temperatures of 10 to 12°Celsius well in the range of the ideal operating temperature of the pXRF. In order to get best results for light and heavy elements an acquisition mode consisting of 30 s at 10 kV beam energy and 30 s at 40 kV was chosen. The total measurement time of one minute seemed to be satisfactory regarding the given environment. Some authors suggest, that even 10 s measurements for obsidian still provide reliable results (Frahm et al. 2014). Without using a tripod, a "stable" configuration regarding the geometry of the instrument and the sample is strictly limited to the attention of the operator. Errors resulting from the change of this geometry are hardly detectable under the usual experimental setup, and applying shorter measurement time would presumably reduce user error.

Figure 21: Profile of ditch 1 at Hornsburg 1 KGA. The marked area indicates the part of the cross section, which is presented within Figure 32 (© LBI ArchPro, M.Kucera).

Figure 22: *In situ* measurements taken from the cross section of ditch 1 of Hornsburg 1 in October 2014 (© M.Kucera).

Measurements were taken from a vertical sequence of sampling points at an average distance of 10 cm for the whole cross section of 3.5 m Measurement points were marked with pins and recorded with a total station (LeicaTCR 1203) with an absolute accuracy of 2cm. The detector window of the pXRF analyzer was pressed firmly to the surface and the instrument held manually as still as possible in this position. Out of 33 measurements only one (FD 100) failed, which was detected only during processing of the data. We chose to use fundamental parameters (FP) for the quantitative analysis. With the FP analysis method, one can choose a “standardless” approach, which is useful for analysis of sediments from archaeological sites where there is no single standard for either the local geology or archaeological features or anthropogenic enrichment.

2.2.4 Calibration

In calculating the concentrations of analytes in a specific volume of a sample, two basic concepts influence the results: the general calibration procedure and correction of the matrix effects. Both depend on the technical setup of the analyzer, the geometry including analyzer and sample, and the composition of the sample. The concentration of a specific analyte is in direct relation to its measured net intensity, a calibration constant for the analyte itself, and a correction factor for the matrix effects. The latter are mainly based on absorption and enhancement of primary and secondary x-ray fluorescence inside the analyzed volume and significantly influence the results for the calculated concentration. The basic and yet unknown composition (including internal geometry and chemical properties) of a material induces characteristic x-ray emission. This is due to the basic concept of x-ray emission based on excitation and emission. When penetrating the sample the primary x-ray fluorescence can also excite other analytes, thus emitting secondary x-ray fluorescence, which sum up within the detected spectra (Rousseau 2006). If the composition of a material is known, standards of exactly known composition could be used to calibrate the results and calculate the concentrations. This approach is often used when the general matrix of homogenous material is well known and only variations of trace elements are expected. For this purpose, also calibration curves based on multiple standards with slightly different concentrations is applied. Unfortunately, many archaeological samples (including artifacts and soil samples) are heterogeneous and standards and calibration curves are not always available. This is not the case for stone, obsidian in particular. For other materials, several calibration methods have been introduced since 1954 (see also (Rousseau 2006).

The fundamental parameter (FP) method is appropriate for most applications and experimental settings. FP takes in account the influence of the spectrometer geometry, the measurement settings and the sample type. The relative intensities based on the fundamental equations, which correlate intensity and concentration, are optimized with iterative calculations, and the FP method can significantly suppress the matrix effect. For the analysis of sediments and soil using pXRF this calibration method provides acceptable accuracy (Han et al. 2006).Therefore, we chose to use FP calibration for the quantitative analysis. For the presented analysis of sediments from archaeological sites where there is no single standard for either the local geology or archaeological features, this “standardless” approach is appropriate. The SpectraEDX software from Bruker provides several standard calibration procedures based on the FP method for the respective spectrometer and experimental setting.

2.3 Data Analysis

After calibration, data were exported and prepared for further analysis with statistical and analytical software. In general, we decided to focus on the analysis of the single elements rather than the chemical compounds. From each recorded spectrum all detected elements, the respective precision and the lower limit of detection (LLD) were taken in account. Data was normalized to 100%, and exported as csv files. General descriptive statistics and cluster analysis were performed in the statistical program PAST v.3.15 (Hammer et al. 2001), and spectral analysis and visualization done in open-source software SciDavis and OriginPro v7.5, respectively. OriginPro supports various statistical analysis and fit functions. For our purposes, linear regression and polynomial fitting were applied. We chose point and line display of the sample points in diagrams for better readability.

In the initial data analysis, we have attempted to ignore potential visual interpretations of the stratigraphic layers exposed during excavation, as the sampling and interpretation strategy might be biased by additional observations. Instead, we focused on characterizing the sediments in terms of elevated chemical elements. By this first visual analysis of the data, tendencies and pattern of elemental distributions and relations were examined. In the following discussion, measurements are compared relative to one another. For a more detailed interpretation of the statistical and spectral results, a separation into the main detected elements (Si, Al, Mg, Ca, Fe and K) and trace elements is presented. For the interpretation, 32 completed measurements were analyzed.

3. Results

3.1 Statistical Evaluation of Data

3.1.1 Summary statistics

Soils are highly spatially variable, embodying both random (e.g. bioturbation) and systematic (soil formation) processes (Jenny 1941). Soils in archaeological contexts are further subject to anthropogenic formation processes (Schiffer 1987). Exploratory data analysis is an essential step to identify potential variability and anomalous values. Standard deviations and range are used to assess variability and predict which elements were most likely enriched due to anthropogenic activity. If values for an element have a low standard deviation, even when compared to local and regional background, then we can infer an origin in the geological parent material (in this case redeposited loess). Conversely, if an element has high standard deviations within a site or feature, then human inputs are a likely explanation. Standard deviations at Hornsburg 1 show that Al, Ca, Fe, Mg and Si all have standard deviations greater than 1.0, and these plus K have a range greater than 1.0. These elements are therefore useful for discriminating between stratigraphic units, and may be (but are not necessarily) related to anthropogenic activities. Figure 23 displays all measured elements with the respective standard deviation indicated with error bars and the min and max values. The great variability of these main elements is clearly visible within Table 5 and by the visual display (Figure 23).

element	mean [%]	σ [%]	min [%]	max [%]	range [%]
Al	13,2	1,4	9,4	15,6	6,2
Ca	18,2	4,7	9,1	32,3	23,2
Fe	9,5	2,7	7,0	22,9	15,8
K	4,3	0,4	3,1	4,8	1,8
Mg	5,1	1,8	1,5	9,8	8,3
Si	47,5	4,1	36,6	53,3	16,7
Ti	1,14	0,10	0,96	1,32	0,37
Cd	0,25	0,04	0,23	0,47	0,24
Mn	0,20	0,06	0,13	0,49	0,35
Ba	0,15	0,08	0,08	0,36	0,27
P	0,15	0,04	0,07	0,24	0,16
Zr	0,097	0,025	0,050	0,190	0,140
Sr	0,058	0,023	0,041	0,179	0,139
Rb	0,030	0,009	0,020	0,073	0,053
Ce	0,023	0,005	0,015	0,036	0,021
Zn	0,020	0,003	0,014	0,027	0,013
Cr	0,014	0,005	0,004	0,022	0,019
Cu	0,014	0,003	0,009	0,025	0,016
Y	0,011	0,005	0,007	0,037	0,030
Ni	0,0067	0,0020	0,0036	0,0112	0,0076
As	0,0054	0,0052	0,0000	0,0187	0,0187
Pb	0,0047	0,0031	0,0018	0,0180	0,0162
U	0,0045	0,0045	0,0000	0,0252	0,0252
Th	0,0041	0,0026	0,0000	0,0144	0,0144
Nb	0,0041	0,0019	0,0017	0,0108	0,0091
W	0,0027	0,0019	0,0000	0,0072	0,0072

Table 5: Descriptive statistics for chemical elements from 32 pXRF measurements at Hornsburg 1. Elemental concentrations are normalized to 100%.

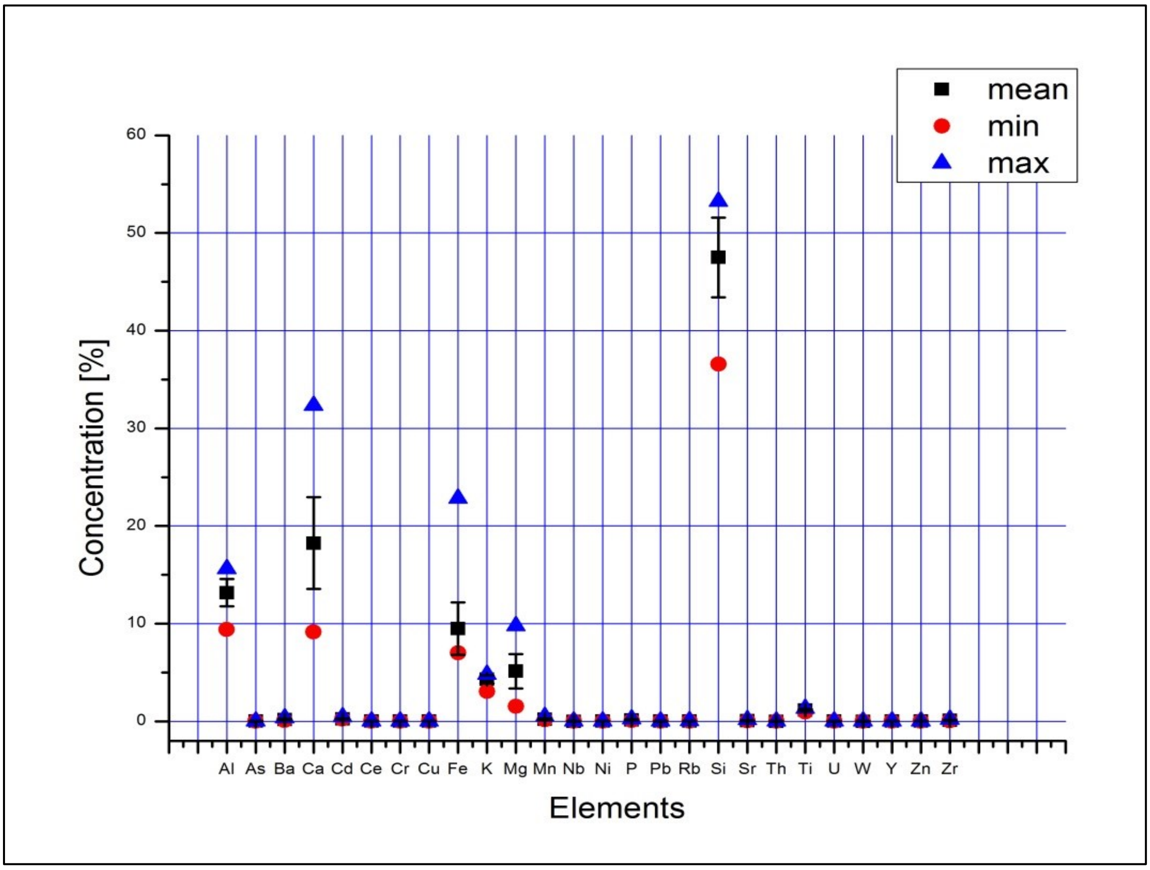

Figure 23: Variability of all measured elements with range and error bars from Hornsburg 1, Ditch 1. The scale is optimized for the display of Al, Ca, Fe, K, Mg and Si.

Great variability of these elements is also examined along the measured line section (Figure 23). The spectra show also an anti-correlation of Ca to Al and the prominent Si, whereas K and Mg are not so strongly related. As the distribution of these main elements varies significantly, different processes of deposition and transformation can be distinguished. Starting at the bottom of the ditch a first class could be located between samples 72 to 74. Between samples 74 to 90, no common tendency is visible. Only Mg produces a stronger signal for sample 84, which might allow differentiating even this second class. After this zone, the concentration of Al and Si decreases significantly (samples 92 to 98), which is also reciprocally indicated by increasing Ca and Mg. From sample 98, Al and Si values steadily increase again, and Ca decreases (compare also Figure 24). From these observations, at least four different classes of soil compositions can be derived.

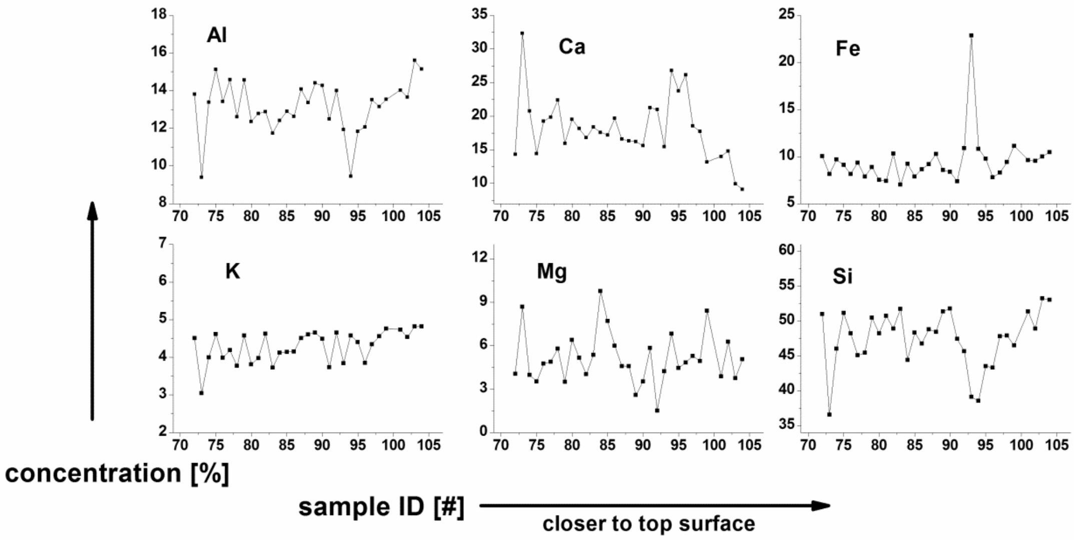

Figure 24: Variability of the six main elements depicted as line graphs, from Hornsburg 1, Ditch 1.

3.1.2 Hierarchical clustering

Next, hierarchical cluster analysis of the multi-element data was used to determine which elements were enriched together. As a data reduction method, cluster analysis minimizes within-group variability while maximizing between-group variability, and assumes that related elements will tend to cluster (Drennan 2009; Rogerson 2001). Unweighted Pair Groups with Arithmetic Mean (UPGMA, or group average) clustering was used. This method defines the distance between groups as the average distance between each of the members. The clustering dendrogram (Figure 25) suggests that Si varies in opposition to other variables. Magnesium and K are very close, and Fe, Al, and Ca are likely to vary together. Euclidean distances between elements with standard deviations and ranges below 0.9 are very small. Therefore, we expect that stratigraphic units can be characterized in part by the variation of Si, Mg/K and Al/Ca/Fe, with possible additional discrimination between Al/Fe and Ca.

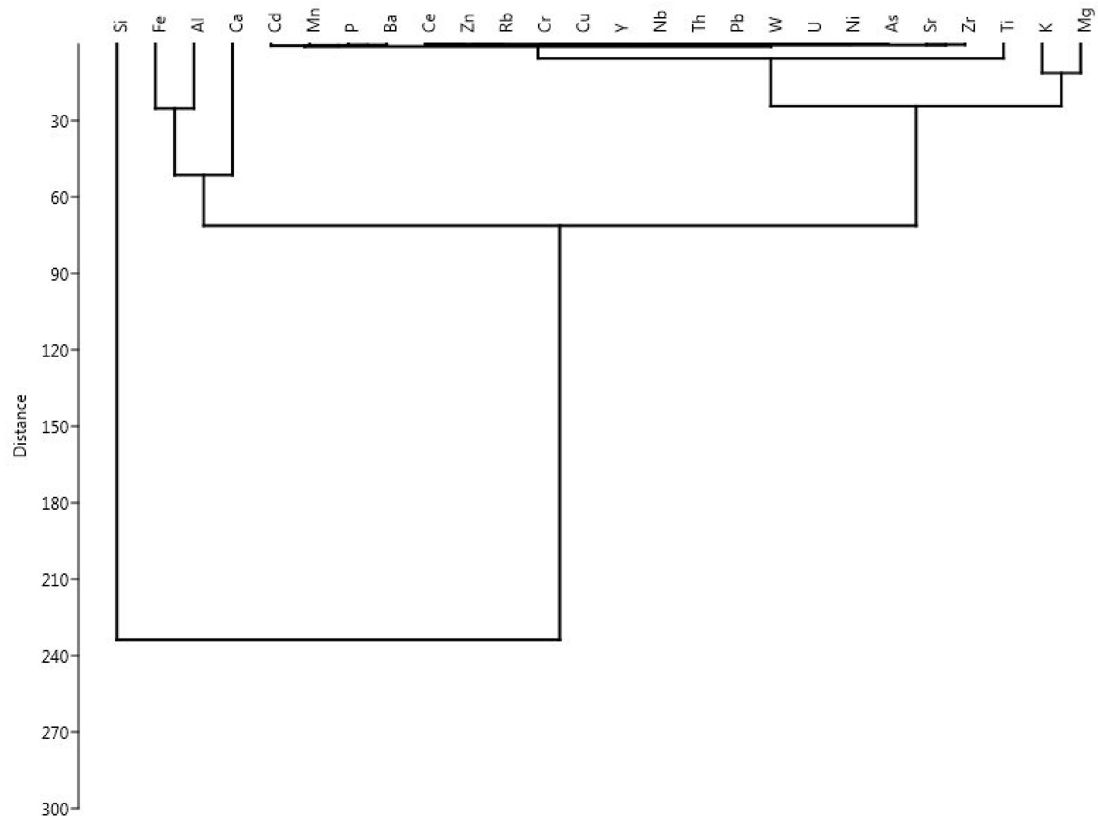

Figure 25: Dendrogram of cluster analysis for multi-element data from Hornsburg 1.

3.2 Spectral analysis and visualization

3.2.1 Phosphates and trace elements

Phosphorus (P), in the form of phosphates, is one of the most important and certainly the most widely used chemical element for archaeological soil chemistry. The primary reasons for this are that P is present in large quantities in organic matter, and therefore added to the soil through most human subsistence activities. Phosphates remain stable for centuries while undergoing little to no depletion from natural soil processes, and are relatively easily extracted and measured, particularly for available, or labile, phosphorous (Bethell and Máté 1989; Holliday and Gartner 2007). In this case study, pXRF values for P were not elevated, and the range and standard deviation were well below our well cut-off and values for Al, Ca, Fe, K, Mg, and Si. Nevertheless, some effects were observed and can be used to argue the presence of a biased distribution of P along the line section. Firstly, we controlled, whether the concentrations were well above the lower limit of detection (LLD), which was mostly below 300ppm (Figure 26). With a mean concentration value of 0.15 ± 0.04% (Table 5:

Descriptive statistics for chemical elements from 32 pXRF measurements at Hornsburg 1. Elemental concentrations are normalized to 100%.) the measured concentrations were approximately five times higher than the LLD.

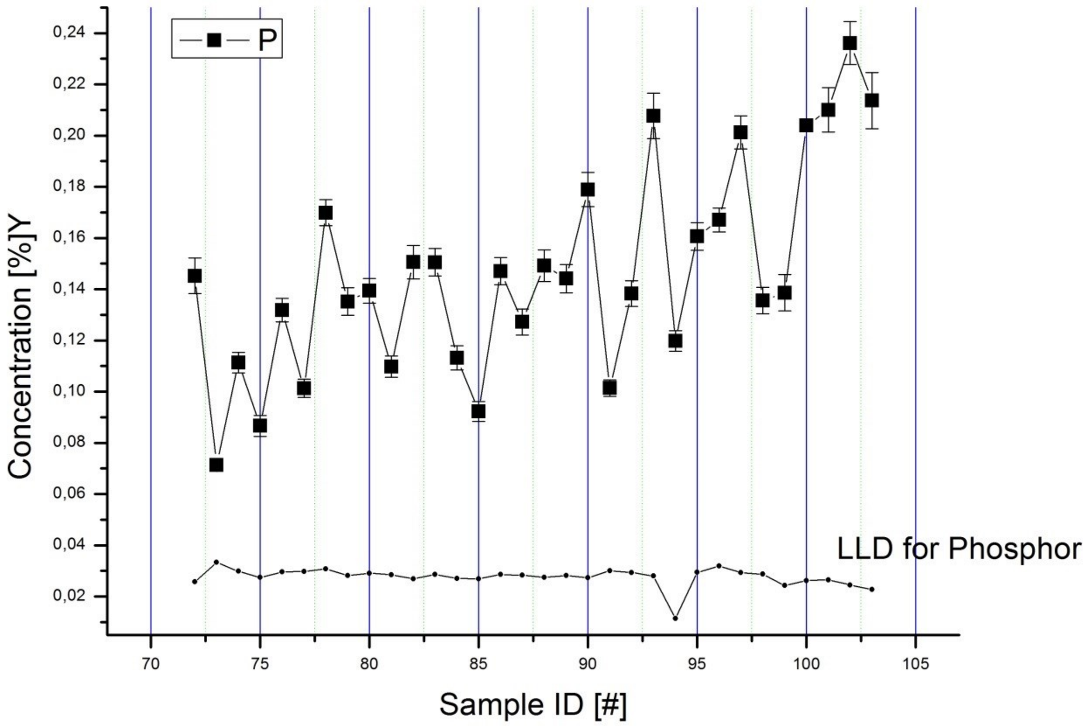

Figure 26: P data from Hornsburg 1. Values are significantly higher than the LLD.

P shows large spatial variability in concentration, which is represented by range and standard deviation. The fluctuation of the spatial distribution is displayed by visual analysis of the spectrum as well. A steady decrease with depth is observable and illustrated by linear regression (Figure 27). A similar effect might be faintly visible for Zn, but is not significant enough and is only qualitatively guessed.

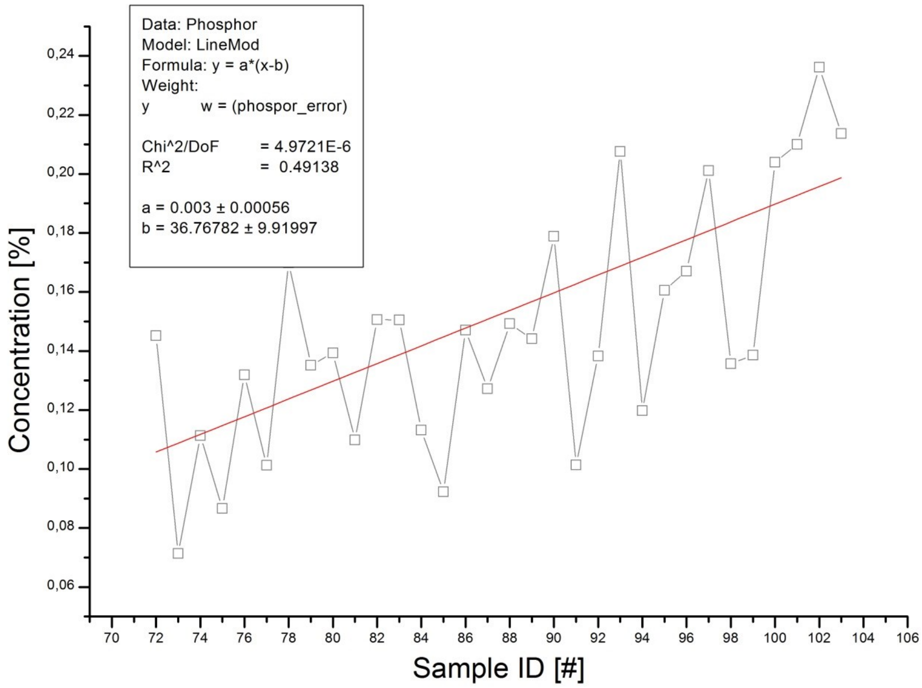

Figure 27: Linear regression applied on the spatial distribution of P based on pXRF measurements from Hornsburg 1.

3.2.2 Other trace elements

The other trace elements are in the range of per mille to several hundred ppm. Only Ti with 1.1±0.1% concentration and range of 0.4% is significantly higher than the other elements of this group. Its concentration constantly fluctuates with a range of 0.37% and seems to be not related to depth or other elements. Only a very faint relation to Fe, Mn, Cu, Ni, Cr, and Th for sample 82 might be mentioned but is only qualitative (compare Figure 23, Figure 28 and Figure 29). Concentrations of Ba, Mn, and Cd are at levels comparable to P, whereas Cd shows only very small variations. Mn relates as expected to Fe. Only sample 94 shows a significant increase of Cd, but also of other elements. This is also partly displayed as max and min values are for some elements out of balance regarding the mean value (compare especially Cd, Mn and Sr in Figure 30 and Figure 31). We will discuss this observation later. The variability of As is also remarkable, although some samples show now presence of As, which was below LLD in these cases. With an average concentration of 0.05±0.05% it is relatively low and close to the LLD and has a high standard deviation. Especially closer to the surface, As could be relevant for the elemental composition characterization.

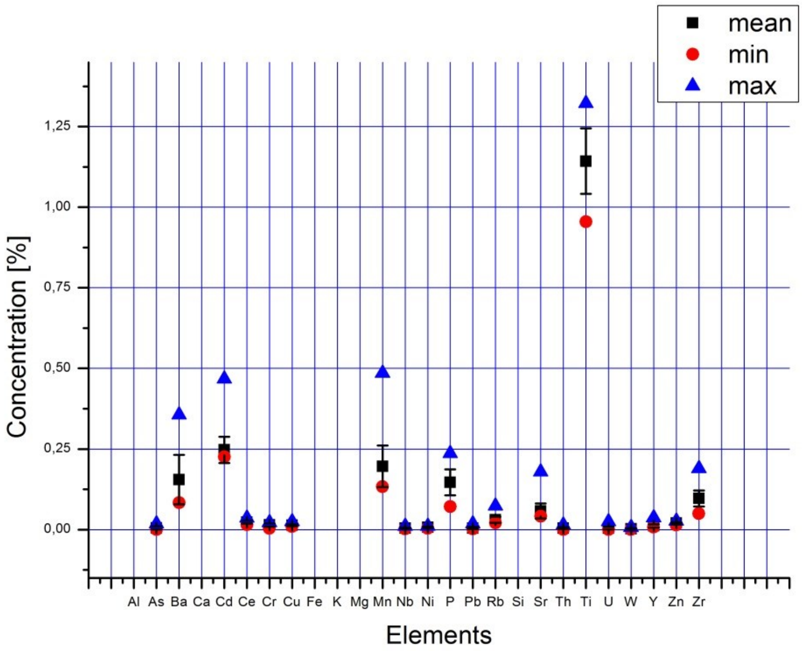

Figure 28: Variability of lower concentration elements with range and error bars from Hornsburg 1, Ditch 1. The scale is optimized for the display of Ba, Cd, Mn, P, Sr, Ti and Zr.

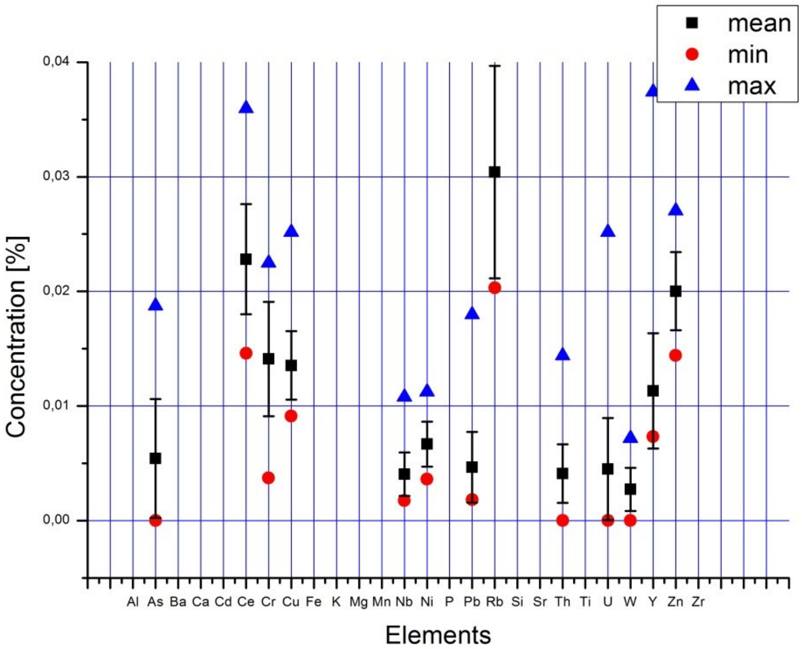

Figure 29: Variability of trace elements with range and error bars from Hornsburg 1, Ditch 1. The scale is optimized for the display of As,, Ce, Cr, Cu, Nb, Ni, Pb, Rb, Th, U, W, Y and Zn.

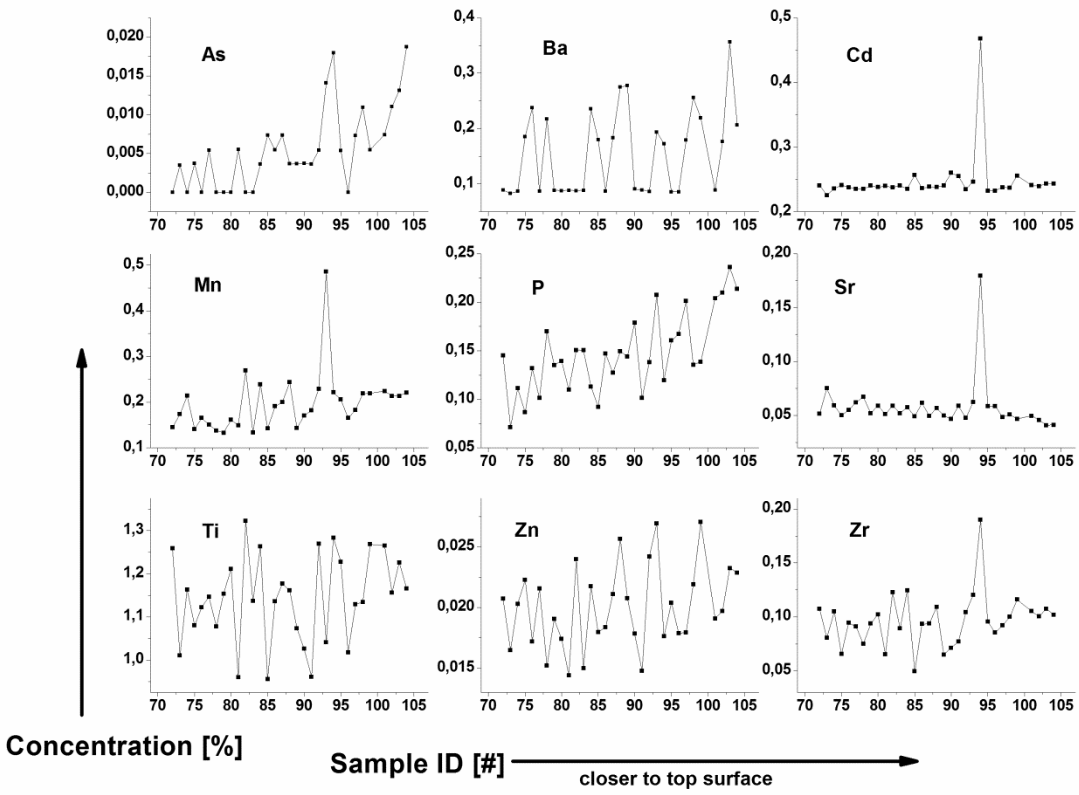

Figure 30: Comparison of minor elements. The scale of y-axis is optimized for every elemental distribution. The spatial development of Mn was used to classify SU. Mind also to compare P and Zn.

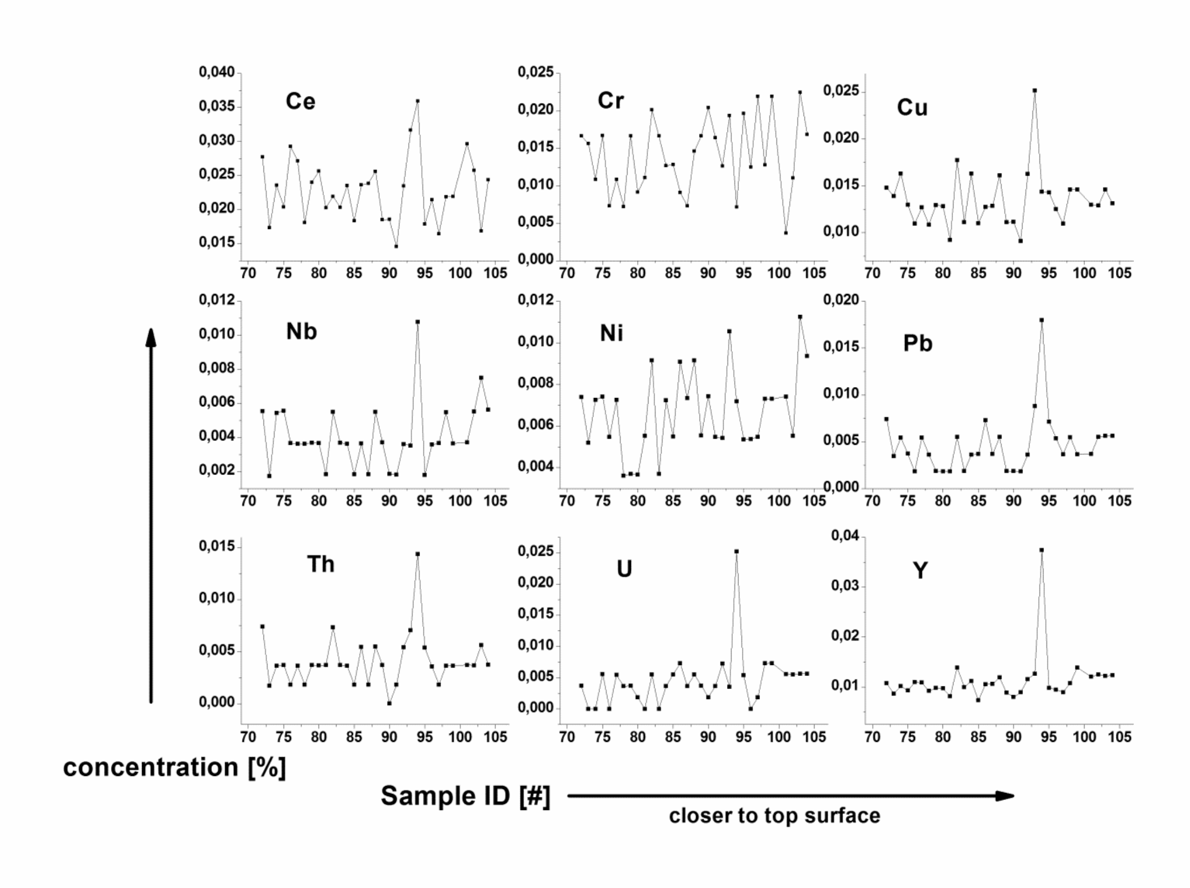

Figure 31: Comparison of minor elements. The scale of y-axis is optimized for every elemental distribution. The spatial development of Cu was used to classify SU.

3.2.3 Classification of zones

One of the major research questions was whether different observed processes of stratigraphic units can be characterized by their chemical composition. During the excavation, 85 stratigraphic units were recorded. This illustrates the enormous range and variety of documented processes and materials. The genesis of the derived stratigraphic sequence is of great importance for an archaeological interpretation of phases of use, reuse, maintenance, and refilling of the ditch. Zones of low sedimentation rates manifesting as thin layers are interspersed with massive erosion events, probably due to heavy rain or artificial and intentional refill. In this respect, one challenge was to determine whether these variations could be also represented by the pXRF results.

For this purpose, the spatial distribution of Si, Al, Ca, Mg, Mn and Cu were qualitatively analyzed. As the cluster analysis demonstrated, these respective results correlate and thus values are not arbitrary. Additionally these elements showed spatially classifiable behavior. Each variation diagram was separately interpreted regarding local fluctuations, extraordinary peaks and development. According to this procedure, four classes were derived for Si and Ca, whereas the spatial distribution of Al, Mg, Mn and Cu seem to represent five classes. Cross analysis of the classes derived from each elemental distribution indicate their spatial correlation. A final comparison with the respective parts of the cross section confirms this hypothesis. Different phases and types of deposits and processes, which can be archaeologically and geologically argued and interpreted, are distinguishable by pXRF data as well (Figure 32). Significant accordance is observable for the transition of class 1 to class 2. The other classes also identify different processes of deposition, for example, class 3 confirms the start of a slow refill of recut of the ditch.

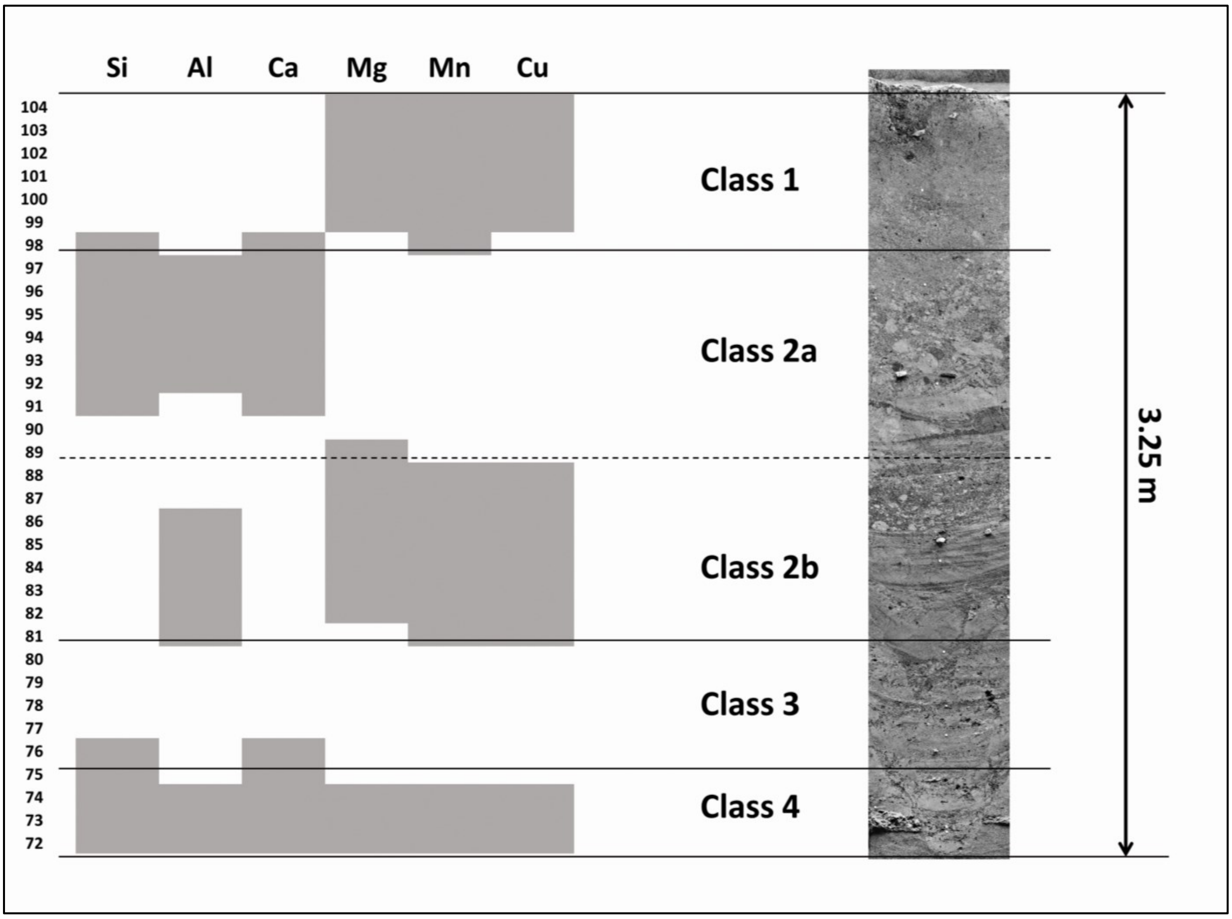

Figure 32: Different classes derived for qualitative analysis of the spatial distribution of elements (© M.Kucera).

4. Discussion

pXRF has recently seen wide application for on-site and in situ analysis of archaeological artifacts and soil. The results presented here are based on surveys carried out in 2014, whereas the first tests were made in 2013. From these first measurements, questions arose about whether data acquired through in situ pXRF measurements can characterize the composition of sediments and stratigraphic units and thereby allow a rough classification of potential deposition and formation processes. The two main considerations regard the practical and theoretical aspects of in situ pXRF for chemostratigraphic characterization.

4.1 Practical and theoretical considerations

Practical considerations included testing the in situ applicability of pXRF within the routine workflow of excavations. Whereas the presented results document vertical data acquisition along a line section of a profile, lateral measurements (line sections of objects) have been performed as well. Since the instrument was operated without additional support, possible influence and respective limitations on the quality of the result was examined. As only one sample failed, manual support was sufficient for measurements lasting up to three minutes each. Later detailed analysis of the results indicates that realistic variations and spatial distributions of observed elements were obtained. Data acquisition of horizontally distributed samples is comparably easier than the recording of vertically aligned samples. The latter was in our case very specific due to the size of the exposed cross section to an absolute depth of about 4.5m. As already mentioned, boards were placed to guarantee stable measurement positions. The overall acquisition time of all 34 samples for the complete documentation of the vertical line section at 10cm spacing including the setup of the instrument and the sample points lasted for 3 hours on site. Compared to the total amount of time used for excavating and recording all stratigraphic units from the ditch to expose the cross section, this is negligible.

A major part of the discussion, which was already carried out on site, regards the representativeness of the measured spectra for a specific area. As the spot size of the used instrument is about $35mm^2$ reproducible measurements also include accurate replacement. The typical soil matrix is characterized by variability. It could be argued whether accuracy and precision of the respective instrument and the experimental setup are below the threshold, where overall correlations of different components of the soil matrix can be observed. Accuracy regarding the multiple measurement of a soil standard over 14 month done by Gauss et al., showed reproducible results

(Gauss et al. 2013). As these investigations were carried out for a standard, compositional variations of natural soil seem to exceed expectable accuracy. Other research compared intra instrument analysis regarding precision and accuracy with other energy dispersive x-ray analysis (Goodale et al. 2012). Goodale and colleagues also warned that instruments might only provide stable and comparable results for the majority of elements, whereas some concentrations are mischaracterized. They suggest close cooperation of archaeologists and manufacturers, as calibration variables and design of the instrument have to reflect archaeological purposes. Results from studies focusing on pXRF measurements of P, as the most used and possibly most significant anthropogenic element, indicate that method of application is critical, and that different equipment and parameters yield radically different results (Frahm et al. 2016; Hunt and Speakman 2015). Additionally, other physical properties, such as soil moisture (Parsons et al. 2013), can influence the results.

Many efforts have been undertaken to enhance the accuracy and precision of pXRF. Even though these have mainly be taken under lab conditions (Johnson 2014), the extreme heterogeneity of the samples interferes with the scientific demands for accurate and precise measurements. This effect is dramatically exacerbated when in situ measurements are carried out. In this respect, a qualitative analysis of results is probably preferable and more realistic. Under these circumstances, the main challenge is to clarify if and to which degree the results represent the actual composition of the soil. The main question is whether results are arbitrary or realistic, and whether an acceptable threshold can be achieved.

We are aware that we are unlikely to retrieve the same set of values if we could measure the 34 sample locations again. Therefore, the question becomes whether a closer analysis of the results indicates a realistic relation to the actual composition of soil. First of all, results seem not to be stochastic, as the main elements are related in an expected way (e.g. Si, Ca, Al and Fe and Mn). Tendencies of the spatial distribution of some elements – namely P – have been detected. If, for example, drift caused by instrument settings over time would have been the cause of the constant increase of P, this should also have been observable within other elemental distributions.

The core advantage of pXRF – measuring various parameters at the same time and place – is also the basis for an inter-elemental analysis. Whereas accuracy and precision might be poor for a single element, inter-elemental analysis is capable of deriving general tendencies of soil composition. It allows defining several classes of material composition along the measured line section. For example, only comparison with other samples and inter-elemental analysis allows critical rating of the material evidence reflected by sample 94. Results of nearly all elements are clearly distinguishable from other samples, which could also indicate an outlier. On the other hand, neighboring samples anticipate this sudden change of concentration. The latter argument supports a significantly different material composition at this location.

4.2 Defining stratigraphic units

As already mentioned, 85 stratigraphic units (SU) have been documented for the excavated part of the inner ditch. Comparing this to the total amount of samples, which have been acquired, results in a mean representation of one sample for three SU. In this respect, different processes can be observed in the XRF data, rather than single SUs. Additionally sequences represented by very thin layers are interchanging with higher deposition rates, especially in the top layers of the ditch. These zones are well represented by the results gained through pXRF. From a qualitative analysis, five classes could be derived from the pXRF data, which are in good accordance with the observed processes. For a more distinct determination of SUs, a higher resolution distribution of sample points is desirable for this specific context. As the observed variations within the stratigraphic sequence outreach limitations regarding accuracy, precision and LLD of pXRF applied within the experimental setup given, measured values are reliable. In accordance to this, the measurement time can be reduced in order to increase sampling rates while still guaranteeing reproducible results.

4.3 Limitations of the method

Not all elements were included in every spectra – this is an inherent limitation of the instrument. This may not matter when focusing on the known anthropogenic elements, but becomes more significant when trying to characterize sediments based on their total chemical constituency, which should be a strength of the method. With a very small resolution, these results are mainly good for initial characterization and may need multiple measurements from each stratigraphic unit or archaeological feature to provide valid results.

Although we did a detailed analysis of the phosphate data, the lack of correspondence between P and other anthropogenically enriched elements, and the low P values derived from the pXRF at Hornsburg 1 support other reports that P measurements are not reliable in all cases. With P being a very important element in archaeological soil chemistry, this result is troubling. We must stress that this will not necessarily hold for every situation. Different instruments applied to different lithologies provide P results that appear to be more useful. An important consideration is whether results from various sites can be compared to one another. Our results suggest that while pXRF has proven useful for quick and dirty characterizations of chemostratigraphic units in situ, it may not be appropriate for comparative analyses in terms of anthropogenic enrichment.

5. Conclusion

The in situ application of pXRF seems to be well suited to get a first qualitative assessment of sediment composition. The method´s strength is in determining multiple elements at the same time, enabling inter-elemental analysis. Therefore, despite the heterogeneity of sedimentary characteristics, in situ measurements provide a first assessment and provide a basis for a sampling strategy for subsequent analyses under controlled conditions. We believe that a lot of archaeological fieldwork is not firstly related to precisely hit a target, but rather to set it up at a scientifically relevant threshold. pXRF measurements allow collection of basic information on site in order to determine further analytical steps. Given the fact that every archaeological site is unique (Harris 1989), research questions and applied methods have to be specified during archaeological fieldwork. For this purpose, even preliminary qualitative knowledge of physical and chemical properties is helpful.

pXRF, like all other analytical methods derived from natural sciences, only appears to be quantitative when applied for archaeological purposes. It is in fact a semi-quantitative method with a large qualitative component, which is partly determined by the heterogeneous character of archaeological samples in general. A more promising approach is the controlled comparative analysis of qualitative datasets. Whereas a complete and absolute display of the composition and chemical properties of soil at a specific moment is nearly impossible, as soil processes are dynamic, a rather fuzzy view of specific properties is realistic. A main challenge of a qualitative inter-elemental analysis is to define a specific threshold for a respective elemental component, rather than increasing accuracy for only apparently quantitative results. Whether observed phenomena are significant and therefore exceed a defined threshold depends on the overall observed pattern, the relation to other elements and parameters and the comparison of these different components. If these methodological limits are respected, pXRF in situ measurements provide a reliable method for an interpretative analysis of soil composition.

Although this paper deals with the application of pXRF, a combination of many methods is crucial for a detailed study of any observed phenomena. Our next step will be to focus on a comparison of the chemical data presented here with the stratigraphic sequence, magnetic susceptibility values, and magnetic prospection data, in order to derive more information about the reliability of the stratigraphic units specified by excavation.

Acknowledgements

The excavation at Hornsburg 1 was carried out by the Vienna Institute for Archaeological science (VIAS) in cooperation with the University of Vienna, Department of Prehistory and Historical Archaeology and the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro, Vienna, Austria). The excavation team consisted of students and scientists from different disciplines, who supported the presented research. We thank also Erich Draganits, Michael Wagreich, Sabine Hruby-Nichtenberger, and the University of Vienna, Department of Geology for use of the pXRF. We especially thank Wolfgang Neubauer for support during data acquisition and data interpretation.

Integrated data interpretation

The huge variety of the archaeological material and the applied multidisciplinary methods motivate integrated data interpretation. Archaeological information is rarely derived from just one data source. As archaeological phenomena are influenced by many different parameters, of which sometimes only few are known or directly observable, an archaeological hypothesis has to include and respect as many available datasets as possible. This inclusion of different results and methods must be correctly defined regarding the practical and theoretical framework. The latter is of main interest for arguing the principles for routines, when different scientific disciplines need to interact. This includes discussing concepts of multidisciplinary and interdisciplinary approaches and collaboration types.

Within the following chapter a possible practical framework for an integrated interpretation will be presented and discussed. From a processual point of view data will be used to segment, classify and archaeologically interpret spatial and temporal entities and their relations. The suggested framework is a GIS-based archaeological information system (G-AIS). This system has to enable the comparison of different datasets and guarantee the reproducibility of gained results. Specific results must be traced back to their origin and to the specific context from which they were drawn.

Basic routines for the interpretation of archaeological entities

As all archaeological prospection data gives first of all a qualitative impression of the archaeological evidence manifested by distinct entities, these data must be quantified regarding their spatial location. To guarantee the reliability and reproducibility of the results a clear separation of segmentation and classification of observed entities is mandatory, based on their physical attributes and their archaeological interpretation.[20]

Segmentation of data

Every archaeological dataset gained by archaeological prospection relies on (geo)-physical data. Once these data are postprocessed, they can be analyzed. The first step is the spatial segmentation of the data, where areas or volumes of the same observable physical properties are grouped. In this sense the data is digitized into spatial objects specified by the same (presumed) physical properties. Segmentation is a process, which can be automated, as the physical (reproducible) contrast of specific parameters is analyzed. Techniques for automated feature extraction are applied, whenever complex data has to be reduced to simple structures (Pregesbauer et al. 2013). The result of

[20] The basic concepts for the four levels of interpretation, which will presented in the following, have been developed together with Wolfgang Neubauer, during an intensive meeting.

segmentation or feature extraction is a strongly reduced dataset, which indicates areas and/or volumes of significant and previously defined contrast.[21]

Classification of data

As soon as the data is segmented, they can be classified regarding their specific physical properties. In satellite remote sensing the classification of segmented entities based on different physical parameters is crucial for the generation of thematic maps. Often two and more parameters can be combined to define respective classes. In magnetic prospection data, typical classes – or attributes – include the origin and type of the magnetic anomaly and its magnetic contrast. For a subsequent integrated interpretation, no classes regarding archaeological content are created. Only physical properties are attributed.[22] Segmentation and classification of the data are the basic archaeologically unbiased steps to prepare the data for archaeological interpretation or interpretative mapping.

Archaeological interpretation – interpretative mapping

Within interpretative mapping archaeological information is related to segmented and classified spatial objects. Also depending on the applied methods this includes the description of archaeological features, structures, distinct and seamless areas. Different types of archaeological information are linked with the respective objects. During the process new segmentation and classification can be created as well. This hierarchical structuring allows the illustration of different layers of varying detail and is crucial for an analytical display of data derived from multiple methodological backgrounds at changing scale.

Archaeological features

This general class represents the basic units of segmentation dependent on the applied method. The smallest achievable entities are the SU derived from archaeological excavations. Archaeological prospection data usually provides the detection of objects of the size of e.g. postholes, pits and kilns, which are typical for the class of archeological features. They are the basic elements that describe the functionality and extent of an archaeological site. A primary task of archaeological interpretation is to make a decision as to which function every observed archaeological feature can be assigned. This information can be derived from shape, size and orientation of a single feature, its spatial relation to other surrounding features and depends also on the dataset under investigation. For

[21] The amount of observed contrast can be crucial to decide which type of feature has to be tracked. E.g. pits located in a paleo-channel of an old riverbed will have comparably higher contrast in magnetic data than the riverbed itself. Also the zooming factor is important for the perception of features of different size such as a pit and paleo-channel.

[22] In some cases this can lead to double naming. E.g. “pit” is primary an abstract description for an object with a specific geometry, but also has an archaeological meaning.

example, a circular feature of approx. 0.5 m diameter visible within a magnetic data, which is also related to others of similar size, could be interpreted as a posthole.

Archaeological structures

Archaeological structures consist of one or more features and are also interpreted based on the spatial neighborhood with other features and structures. Basic information can also be derived from other sources (e.g. topography, hydrology). The spatial extent of structures is often not as clearly definable as the location of features. For example, several distinct features, which can include postholes and small ditches arranged in a specific pattern, can indicate the structure of a house. This arrangement (regarding also orientation and size) can identify different types of houses, which can be representative for a specific archaeological period or even phase. Nevertheless the physical boundaries of a house are more likely to be estimated. It is often hard to tell whether the roof of a house has covered a larger area than the size indicated by the pattern of postholes. In general the reconstruction of prehistoric houses relies on ethnographic analogies, the results of experimental archaeology, occasional depictions (wall paintings, petroglyphs) and rarely found wooden parts of constructing elements (shingles, rafters, wattling). All this additional archaeological information leads to a biased interpretation of a possible spatial extension of the respective structure based on expert knowledge. All this background data can be referred to as metadata, which has to be related to the spatial information of the structure.

The creation and definition of archaeological structures is crucial for the further functional classification of an archaeological site or landscape. It is also an important concept for the analysis of the temporal relations of observed features and structures. Most likely the observed archaeological evidence represents succeeding phases of different houses and further infrastructure. The stratigraphic sequence or temporal development of, for example, a village can also be derived from the spatial superposition of structures such as houses. Once single features are grouped within superordinate structures that can be temporally sequenced, they can be also related to a specific period or phase.

Distinct areas

Distinct areas define areas related to a specific function. This includes general living, ritual and infrastructural areas, e.g. several houses grouped as a settlement area. In relating houses of different phases with the respective settlement area, the spatio-temporal development of such an area can be described and analyzed. Distinct areas can also mark different quarters of a town, indicating trading markets and living areas. They are also the basis for the spatio-temporal analysis of landscapes regarding traffic and resource management. For the definition of the spatial extent further data sources can be used including topographical data, geological data (resources) and hydrological data.

Distinct areas include only areas directly used or influenced by human societies. They are distinct in this sense, as their physical boundaries have to be mostly estimated.

Seamless areas

The basic concept of seamless areas is to derive a complete hypothetical segmentation and classification of an archaeological landscape within a defined time interval. This also includes areas not influenced by human societies during the respective time interval. Although this interpretation must be highly hypothetical and has a strong theoretical and abstract character, it is a mandatory step in investigating and formulating principle rules for the spatio-temporal development of landscapes influenced by humans. In the initial phase of exploration, a thematic map indicating seamless areas will show a lot of white spots within archaeological landscapes. But only in defining even these white spots with a basic description (e.g. "unknown function"), these areas can be included within spatial analysis of the whole archaeological landscape. Even unused land can have an important protective function or can channel trade.

Figure 33: Schematic illustration of hypothetical features, structures, distinct areas and seamless areas. Mind the not defined area within "seamless areas" (© M.Kucera).

Archaeological information system

"In other words, I want to get away from a 2D archaeology altogether. I want to move to what is essentially a 3D recording paradigm. But of course I don't even want to stop there: I need my 3D GIS to be able to simulate post-depositional transformations, taphonomy… so what I really want is 4D. And so I'm not talking about GIS any more, but some sort of AIS (Archaeological Information Systems)." Geoff Carver in (Carver 2005), p.1.

This statement by Geoff Carver from 2005 illustrates the basic motivation to create AIS for the documentation and analysis of archaeological data. In claiming the implementation of a temporal component, Carver exceeded the general concerns of the archaeological community. Only recently a 4D AIS has been described by Roo et al. (Roo et al. 2014). Carver highlights the similarities of the properties of archaeological and geographical data. He concludes that an information system dealing with archaeological data must be based on GIS. Furthermore the documentation techniques relying on the principles of stratigraphy first introduced by Harris in 1979 (Harris 1979) need to be adapted to volumetric data. Finally a temporal model has to be established that fulfills the demands of a theoretical framework for a 4D AIS (Carver 2005).

Within this section recommended components of a 4D AIS will be presented, including a basic description of GIS and the design and functionality of geodatabases. To get hold of the temporal component, the theoretical framework of time-interval-based stratigraphic sequencing and the practical implementation of time within AIS will be discussed. In order to compare and interpret different datasets visualization concepts will be suggested.

Geographical Information System

A modern geographical information system (GIS) manages, organizes, analyzes and visualizes geographical and geographically related information and spatial data. It provides computational tools for the analysis and display of the collected data and their spatial relations and derives new information based on that. Basically it is a tool to create as well as analyze new geographical content and display the results within respective maps. When GIS is used within archaeological and historical context, a brief outline of the historical development of GIS is of interest.

A first step towards the creation and design of geographic information systems (GIS) is the display of the earth´s surface within 2D maps. This is at first glance a very simple demand, and reflects the need for the orientation of humans within the landscape. Depicting landscape and information related to it has always been of importance in respect to communication. No matter if it is geographically correct or an abstraction, a map shall support orientation. In a historical context, maps also reflect the awareness of the "world" at a moment in time and for a specific society (Sonnabend 2007). Under these circumstances the term "world" can be separated from "landscape". This differentiation is very important, when archaeological landscapes have to be interpreted. Observed phenomena can also reflect the world how it might have been experienced by the ancient societies under investigation. In this sense GIS is already embedded in archaeology, as geographical information has always been a basic concept of human societies. It can also be argued that the impressive cave paintings from Paleolithic times illustrate the basic concern of human beings for positioning themselves within the universe and communicating this position and further information. In ancient times, a lot of books and maps were created to provide knowledge regarding topography and information of distant areas. Some of these have been influencing human societies and their perception of other regions and societies for centuries.[23] One of the most important pieces of literature of European history is the Odyssey by Homer. At first it seems to be merely an enormous piece of wonderful lyrics illustrating the perils of Odysseus on his way back home to Ithaca, but it is also an elaborated nautical description of sea routes and harbors (Bradford and Güttinger 1964). In the starting time of the Greek colonization of the Mediterranean this was probably the main important factor.[24]

One of the first successful examples in science when a map was used as the basis to illustrate spatial distribution of a specific type of information, were the investigations of John Snow in 1854. When London was plagued by cholera, Snow tried to discover whether a spatial pattern of the cases of cholera could be found. He used a map of the specific quarter of London (Soho) and marked all addresses where people had been suffering from the disease. With a "cluster analysis" derived from this map, he was able to locate the source of the disease – a water pump at Broad Street (Snow 2008).

The modern development of GIS started in the early 1960s, when the management of geographical data was started to be supported by computers. Although the theoretical mathematical basis of spatial analysis was already provided earlier, computer technology set the fundamentals for realizing the calculation and interpretation of multiple datasets. In this regards, the creation and application of GIS was always related to the design of respective databases – so-called geodatabases. A basic demand of every GIS is the representation through a geographical coordinate system. At the latest,

[23] This illustrates how mind breaking illustrations can be and how important it is therefore to be aware of this phenomenon, also regarding the visualization of scientific results. In the context of virtual archaeology one has to be very careful to indicate the hypothetical character of every visualized interpretation. The situation gets even more complicated when results are based on different methods. Scientists have to be aware of the power of depicted ideas. Once a handy image is presented, it is fascinating how hard it is to get rid it. Nowadays most people are convinced that dinosaurs and cavemen didn´t meet (despite of the "Flintstones", but Viking helmets with horns are still a favored picture).

[24] It is also a very good example that simple story telling might get boring, but providing knowledge is always of interest. Nowadays we would talk about edutainment in this context.

when data is correctly embedded in a GIS, they are georeferenced. This means that information can be identified and traced by its geographical location.

Typical input formats include vector and raster data, from which new data can be calculated. Vector data represents a datatype used for spatial segmentation, e.g. polygons, lines or points which identify a discrete spatial element to which information can be related. Raster data is best suited for displaying a continuous type of information based on pixel information. This might be images of any kind (geophysical data, aerial imaginary, but also densities of distribution of finds and samples etc.), which also can be analyzed by GIS tools. For example, topographical data could be displayed in the application of different visualization filters. All these data can be analyzed regarding their spatial relations and correlations and are referred to as layers in GIS. Out of one or more layers a new layer can be calculated in applying different spatial analysis tools. Through the dynamic display and analysis of different layers a wider range of data and their co-influence can be overseen and interpreted at the same time (Di Hu 2011).

For the investigation of archaeological research questions, every layer might also represent a specific period in time. This fact is stressed by Di Hu in contrast to the traditional archaeological approach in respect to stratigraphy (Di Hu 2011). Introduced by Allen (Allen 1983) a time interval-based approach is suited for a far better description of the temporal relations than the more simple time model including the concepts of earlier, later and contemporary.

Although GIS is basically designed for the spatial analysis of geographical information and entities, a lot of recent applications illustrate the necessity for extending the capabilities of GIS towards a temporal analysis. Basic concepts for the implementation of time into GIS have been introduced (Tuan Anh et al.) and have recently gained awareness in the archaeological community (Roo et al. 2014). This development is crucial for every application where information varies regarding a specific location and time.

GIS and archaeology

Since the late 1980s GIS has been applied for archaeological purposes. Although some archaeologists still tend to understand GIS as a map making tool, the power of GIS regarding spatial analysis is mostly appreciated. Its suitability for landscape archaeology is also illustrated by Allen et al. (Allen et al. 1992). During the 1990s the usability of GIS was widely discussed. Based on the concepts and ideas developed by New Archaeology or processual archaeology (Bintliff 1996; Binford 1969; Willey and Phillips 1958), the computational power of GIS was recognized for studying mathematical solutions and routines for modelling observed processes. Agent-based modelling became very popular during this time. Nowadays most of GIS functionality is applied to study archaeological evidence. This includes acquisition, manipulation (e.g. converting datatypes, georeferencing, rectifying, etc.), management, spatial analysis, visualization and automated processing of archaeological data.

The degree to which the application of GIS influenced the development of archaeological theories is arguable, but its practical impact for daily archaeological routines is evident. Regarding theoretical improvement, Di Hu has highlighted that - although theories are only made by humans and never by concepts - archaeological theory has benefitted a lot from the introduction of GIS functionality. Di Hu sees an increasing trend in GIS-based studies, also because of the intrinsic spatio-temporal character of archaeological research. He further remarks, "if such a trend continues, and more researchers learn GIS methods, we can expect to see more communication between archaeological specialists as well as with other disciplines, leading to acceleration in the generation of theory (Di Hu 2011)."

Data management – geodatabase

Archaeological datasets consist of various types of data originating from different disciplines. One of the main archaeological concepts is to compare different phenomena and to look for analogies and patterns. This is a challenge if a dataset is relatively small, but typical archaeological datasets include multiple spatial and temporal information. Another important aspect for archaeological databases is to archive artifacts and their archaeological descriptions in order to guarantee accessibility and comparability. This results in enormous digital catalogues, which also provide the chance for spatio-temporal analysis on the artifact level (Stadler 2014).

Intelligent data management regarding the archiving strategy and the availability of data is crucial for archaeological interpretation routines. The design of a database (or geodatabase) presupposes possible workflows of interpretation and respective results. Besides that, the main issue of a database is to provide a secure, stable and compatible archiving structure for the archaeological data (compare also (Niccolucci 2016; Hiebel et al. 2016; Binding 2010). As archaeological data are always related to a geographical location they are also geodata. GIS supports the creation of geodatabases. As ESRI ArcGIS Desktop 10 was used for the presented work the following general descriptions of the properties of a geodatabase are related to this software.

A geodatabase is, first of all, a simple container for geodata based on a file database. It relates different types of data (raster and vector data) to additional information and metadata and can used by an arbitrary number of users with specified rights. Whereas file geodatabases are easily set up, the functionality of a server geodatabase is more powerful regarding accessibility, data security and redundancy, multiple user applications and the publication of results. For both types the basic components are the same. Each geodatabase consists of one or more datasets represented by feature datasets, geometric networks, simple networks, terrain and topology.

Feature datasets unify several related feature classes, which have the same spatial reference (i.e. use the same geographical coordinate system and projection) and are located within the same area of interest. Feature classes can be represented most likely by vector data including point, line and polygon. Each feature within a feature class can have several attributes. For example, an attribute field of a magnetic anomaly derived from magnetic prospection data could be "type", with predefined values (attributes) ranging from strong to weak, positively or negatively magnetic.[25] These predefinitions can be preset within a domain. A domain is a list of values related to an attribute of a feature. These values can either be associated with coded values, which are most likely text, or a value range (integer). Domains are an important concept to guarantee data integrity.

Geometric networks are used to model resource flow and can be associated with the entities being transported. Usually this includes, for example, electrical lines and water distribution, and can be applied for various purposes in archaeology including trading routes and also the infrastructural analysis of ancient towns. Based on this, a network analysis can be initiated. This could be also applied for migration studies and social networks of ancient societies (Borck et al. 2015).

Networks represent the connectivity of lines and points. They are best suited for the description of a road system. Analysis is not based on additional information regarding what is, but rather where it is transported.

For the representation and analysis of topographical information **terrain datasets** are suited. They are based on TIN-surfaces (TIN – triangulated irregular network) calculated from 3D datasets, originating from topographical surveys (airborne and terrestrial laser scanning, image based modelling, etc.) and are also related to other feature classes present in the same dataset, e.g. the distribution of artifacts of the same type used to specify a terrain class.

Within a dataset, **topologies** help to specify the spatial relations between two or more features. This is a very helpful functionality in testing, for example, the spatial superposition of archaeological entities. It is even more important for testing presumed concepts of the usage of archaeological

[25] A feature class could also be characterized as a table of rows and columns, where geometry (predefined by ArcGIS) and attribute (defined by user) information is stored.

landscapes. Infrastructural relations can be examined and the validity of presumed boundaries tested on the basis of topologies.[26]

The design of a geodatabase depends on the input formats and datatypes to be used and analyzed and the “products”, which are often related to the presentation of the results within maps. This is also illustrated by another practical functionality of the ESRI package, namely the possibility to publish results online and make them accessible for a predefined community of users. Preliminary results can be discussed online and interpretations modified. All presented results are reproducible regarding their origin, as metadata is always available. Changes can even be made directly within the geodatabase, if it is server-based and the necessary rights are provided.

Recording and representation of the temporal aspect

Time regarding a single archaeological entity

Every archaeological entity can be specified by or related to a specific time interval. This is valid for artefacts, biofacts, manuports, but also processes, deposits and architecture. For the start and end dates several aspects have to be taken in account. In general three phases characterize an archaeological find or findings. The first phase can be considered as the time interval representing production and use of an object. The first transition is when this object is deposited. All primary information and knowledge of production and use are hereby lost. The second phase is the deposition process, where the object is superimposed upon soil transformation processes. Usually this occurs under minor human influence. The second transition is the process of detecting and recording. If this is done through an excavation, all depositional i.e. stratigraphic information will be destroyed through the invasive excavation procedure. Accurate 3D recording of the revealed stratigraphic units (SU)[27] supports the generation of a stratigraphic sequence, which represents the discrete progress of the excavation (Doneus and Neubauer 2006). Although the main aim of every archaeological excavation should be to reveal the sequence of the hidden stratification, the excavation itself is already an interpretational process (Kucera and Löcker 2009). It has to be presumed that the documented SU correlate with the originally “true” stratification prior to

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[26] Whereas a single feature like a pit or posthole is clearly visible within one or more archaeological datasets, the extension of a house generated out of these features is relatively less accurate. It indicates more likely an area where a house might have been. It becomes even more complicated when the functional area “farmstead” has to be depicted. Topologies help testing various assumptions regarding the extension of a specific area in relation to others and respective attributes and dataset classes (e.g. topographical data represented by a terrain class).

[27] Compare also pp. 19, where the methods and techniques applied for archaeological excavations are described.

excavation. The third and final phase, which characterizes the temporal development of an object, is when its primary functionality regarding production and use is reconstructed (Kucera 2004).[28]

This very simple model does not reflect all possible details important for the characterization of a time interval related to a single archaeological entity. An object can be used, lost, found again and reused many times. The same is valid for archaeological structures. It is a widely observed phenomenon, for example, landmarks and borders have been respected for several reasons over a long period. This could be related to physical reality, such as an earthwork, which was once probably used as a fortification, later abandoned, but visible within the landscape for a long time. Other areas might have been avoided for more abstract reasons, such as because they are affected by a taboo. Examples to illustrate this are manifold and provided by social anthropology as well(compare also (Mattheußer and Sommer 1991). This suggests that a valid interval-based time model should be capable of testing and manipulating presumed start and end dates of intervals. Whereas for a single archaeological entity this is nearly impossible[29], this could be done based on the comparison and relation to other archaeological entities.

Temporal sequencing of archaeological entities

Traditionally the temporal relations of archaeological entities are represented by the attributes earlier, later and contemporary. This concept is especially used for the temporal interpretation of a stratigraphic sequence derived from an excavation.[30] SU are mostly related to various processes implementing a time interval to be representative for the temporal properties rahter than just a moment. The same is valid for the interpretation of different phases[31] regarding the construction and use of buildings and settlements. Phases are related to specific time intervals, which can interfere with each other. An interval-based approach for describing temporal relations seems to be

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[28] It must be stressed that every interpretation regarding production, use and purpose of an artefact or structure is based on the experience and personal environment of the observer. A suitable archaeological method to reveal unperceived aspects is experimental archaeology. Within this archaeological discipline several theoretical concepts can be tested within an experimental approach. Results gathered from experiments can be used to interpret archaeological evidence. It could be recommended to every field archaeologist to erect a post in order to realize the limiting physical demands (e.g. relation of post diameter and length to the size of the post hole, placement of stones to fix the post, etc.). Although the human perception of the world has changed, the laws of physics have not (Kucera (2004)).

[29] Only possible when absolute dates are provided.

[30] It is very critical for the temporal interpretation of a single SU recorded by an excavation. If the dating of this SU (deposit) is only based on the embedded material, it must be realized that dateable material (including artifacts and ecofacts) can be earlier, contemporary and - in contrary to a general assumption - also later. This is due to the interpretational character of an excavation. SU are defined by the excavation and do not necessarily need to represent the true stratification.

[31] Archeological phases can be distinguished from structural phases. The fundamental temporal principle in archaeology is based on the periodic system dividing the history of humanity into three ages (stone age, bronze age and iron age) with specific periods (e.g. Hallstatt period, La Tène period, etc.) and phases (subdivisions of a period).

obligatory. In contrast to a simple point in time, time intervals can be superimposed in various ways defined by Allen´s interval algebra (Allen 1983). This concept is crucial for understanding the interrelation of different processes and temporal sequences in archaeology and also history. Recently Drap et al. presented an interval-based approach for the temporal interpretation of different architectural phases observed within a medieval building. The authors are aware that the presented results are comparable to a paradigm change regarding the existing common temporal reasoning in archaeology (Drap et al. 2017).

Synchronisation of sequences

From the perspective of a single stratigraphic sequence derived through the (partial) excavation of an archaeological site, a local chronology of observed entities could be displayed. The situation begins to become complex when multiple stratigraphic sequences must be temporally synchronized. This is basically done by comparing different material properties. For example, if pottery type A is found at sites X and Y, the respective SU are contemporary or related to the same time interval. Site X and site Y are attributed with the same time interval (or archaeological phase). Nevertheless it could be argued that specific pottery produced at site X had to be transported to site Y, which indicates that the documented phases can´t have the same starting time. This dependency can also be extended towards more abstract immaterial concepts such as conceptual ideas or political aspects. It is basically a question as to whether the travel time of information for a specific content between the two sites can be determined or not. Missing material evidence for interrelations of phenomena observed at the two sites does not mean that they did not exist.

From these arguments the general question can be derived as to how and if stratigraphic sequences, each representing a local chronology of events and processes, can be correlated. Each sequence or Harris matrix (HM) represents spatio-temporal relations of SU. The spatial and temporal component of each SU is related to a specific uncertainty, respectively, fuzziness. The spatial uncertainty is related to the precision and accuracy of the recording technique and the subjective expertise.[32] Once an HM is temporally interpreted, each SU is defined by an assumed start and end date, with varying fuzziness. All properties and relations of a HM can be tested regarding the mathematical validity of an HM, as SU in physical contact have strict superposition rules. In this sense an HM has to be valid before it can be compared and synchronized with another one.

[32] What is found and documented especially during an excavation highly depends on the personal expertise of the excavators. It is first of all related to the principle visibility of archaeological features and their material contrast. Besides natural human senses, artificial sensors (measurement of susceptibility, magnetic prospection, etc.) are used for the physical segmentation and classification as well. Although it would be a huge advantage to precisely pin down spatial accuracy for every SU, it normally can only be estimated for a larger area and based on applied recording techniques.

A concept attempting to implement temporal uncertainty was presented by Crema et al. It basically relates archaeological events to a time-cube, where the x- and y-axis represent spatial coordinates and the z-axis time. Archaeological events[33] are represented within this model by a projection of single events onto a plane coplanar with the x- and y-axis. Usually the temporal depth of archaeological events is lost and events seem to be contemporary. Within the time cube model, each event is identified with a time interval of varying length. For spatio-temporal analysis and the synchronistaion of events (or stratigraphic sequences) the certainty of a presumed time interval is crucial. Certainty can be quantified in defining a probability weight for the respective interval according to the aoristic weighting method (Ratcliffe 2000). The weight factor (ranging from 1 to 0), as presented by Crema et. al, for a time interval Δt of a specific event *E* is related to the time span and the *terminus ante quem* (β_{E}) and *terminus post quem* (α_{E}) and given by:

$$W_{\mathrm{E}}(t_{\mathrm{n}}) = \frac{\Delta t}{\beta_{\mathrm{E}} - \alpha_{\mathrm{E}}}$$

Aoristic weighting is also based on a simplified model which presumes that the probabilities for the relation of a specific time span and an event are equally distributed over time. Additionally, the *termini post* and *ante quem* must be known (or at least estimated). It defines a weight for a subdivision Δt of a given time interval represented by the two termini and only depends on its minimal temporal resolution. Nevertheless it introduces the specific demands for implementing and modelling temporal uncertainty in archaeology (Crema et al. 2010).

As the temporal properties of an archaeological event are representative for a specific location, this event or phenomenon is characterized by its location and time. As long as an event E_i at a specific location $\mathbf{x}_i$ is not synchronized with other events E_n, it has its relative time t_i. This functional relation can be expressed through $E_i(\mathbf{x}_i,t_i)$. Every archaeological event provides information propogated with a specific velocity, but limited by the speed of light. Two events interfere not instantly, but after a specific time interval, which is related to the propagation velocities of both events. These velocities depend on at least 3 factors: on the type of information (the medium of communication), how it is transported and where it is transported. For analyzing these transport phenomena diffusion models can be used.

In 1974 Noble was able to show that the application of a diffusion model for analyzing the dispersal of the plague in Europe from 1347-1350 AD was able to represent the documented spreading. He found that estimated propagation velocities of information of approx. 100 miles/year resulted in the

[33] Crema et al. refer mainly to archaeological events in their paper. A purely temporal sequence of archaeological events can also be represented by a HM.

observed distribution pattern. As information during medieval time was mostly provided personally and personal contact for the infectious disease is necessary, this estimation fitted perfectly (Noble 1974).

Recent investigations also include models of varying propagation velocity to perform spatio-temporal 2D simulations. Influencing factors include spatial information regarding trading routes, natural and political borders, population density and starting points of the disease (seaports). The transportation flux along a (trading) route within a respective time can be represented through the infected people travelling and the type of route, which correlates with a spatial gradient (Silva 2016).

$$\frac{\partial I}{\partial t} = \nabla . D \nabla I$$

The diffusion coefficient D is given by (Silva 2016):

$$D = \frac{f d^2}{2\tau}$$

f is the fraction of those people of a population from a specific location travelling a distance d within a time τ. The results gained by the spatio-temporal simulation based on these parameters showed good accordance with historical data regarding first occurrence of the disease in towns and mortality rates (Silva 2016). This example also highlights the correlation to network analysis as provided by GIS in respect to the determination of propagation velocities.

Harris Matrix composer

In order to control the temporal component within AIS, respective tools capable of communicating with GIS must be provided. At archaeological excavations software tools have been used for the last decades to display and analyse the recorded stratigraphic sequences (HM). One of these tools is the Harris Matrix composer (HMC) developed and presented in 2007 (Traxler and Neubauer 2008). This first version (HMC V2.0b) supported the synchronisation of different SU in respect to the traditional temporal concept. It also provided a mathematical validity check of the sequence. Attributes of the SU could be stored and related to additional archaeological information.

Recently HMC was modified for the display and analysis of interval-based temporal relations. Introducing also a new temporal model, it was renamed HMC+. Each SU can be temporally attributed with three hierarchical time lines (age, period and phase) and a time interval. Time lines can be defined for every project. The start and end dates can be individually set and correlated with the source of the respective temporal information. SU can also be grouped, which enables a spatial hierarchical display of stratigraphic sequences. In particular, HM of long-term excavations are sometimes difficult to be visually interpreted, because of the enormous amount of documented SU. HM consisting of more than a thousand SU are quite common. A grouping of SU in superordinate objects and structures is extremely useful in guaranteeing clearness. In interfacing GIS and HMC+ a complete 4D analysis solution can be presented as a basis for spatio-temporal analysis.

Geodatabase management and automated segmentation

For the integrated interpretation of multiple datasets, these data have to be uploaded into a prepared geodatabase. As every archaeological context is unique also in respect to the variety of applied methods, respective geodatabases integrating raster data can be optimized. As raster data demand the most storage space, the geodatabase can be limited to the amount of raster data needed for a specific research question and area. For this purpose a GIS extension capable of creating predefined geodatabases is an essential tool, realized through ArchaeoAnalyst. This software was developed by the LBI ArchPro as a basis for standardized data analysis routines. Once data is processed according to the workflow for every applied method it can be uploaded to the geodatabase. In addition to the raster data a geodatabase including feature classes (mostly polygons, but also point and line data) can be generated. This interpretation geodatabase is prepared for a specific archaeological context in respect to the types of raster data, the applicable attributes of expected archaeological features and structures and their respective domains. For example, the coded values defined by a domain for feature attributes mostly depend on the culture under investigation. Domains needed for the description of archaeological features within, for example, a Roman context vary from other periods, as well as urban and rural environmental settings. Predefined interpretation geodatabases are therefore very helpful.

A very important tool for the rationalized segmentation of magnetic data is the automated detection of iron parts and the automated segmentation of pits based on feature extraction (Pregesbauer et al. 2013).The basic magnetic properties as well as their shape and size of these objects were used to define their location. Whereas the location of iron parts is comparably simple (looking for clearly defined dipoles with no preferential orientation), the detection of pits involves more parameters (magnetic contrast, size, shape). Other parameters such as orientation can be used to filter the resulting polygons. Based on these filters a classification of the automatically detected features can be achieved.[34] As manual segmentation of magnetic data from large areas is time consuming, support from automated processes is extremely helpful. Nevertheless the detected features have to be manually classified and archaeologically interpreted.

[34] For example, a cemetery can be detected automatically, when the parameters are set to the usual size of a grave. Under these circumstances the orientations of the pits also play an important role. Often the shape is also a source for a temporal interpretation. Both shape (elongated or round) and orientation can indicate cultural and temporal relations.

For the analysis of GPR data ArchaeoAnalyst provides tools for visualizing time slices. The signals from specific depths can be summed up to maximize the contrast of features. The time gate, which represents a focus of depth, can be individually set, visualizing only a thin section or more of a volume of the 3D GPR dataset. Preliminary interpretational work proofed the usability of animating the time slices. In zooming through the succeeding time slices the 3D character of the observed features can be better observed. Especially for the interpretation of GPR data, the subjective ability, of imaging 3D relations derived from 2D data, which depends on the imagination skills of the respective scientist, is a limiting factor. This recently was the impetus for devoting a lot of effort towards the development of 3D analysis tools for deriving and visualizing iso-surfaces from the 3D data block (Goodman and Piro 2013).

Integrated data display

The raster data is based on a multiple set of methods revealing different information about archaeological evidence. Basically the contrast of this evidence and the background is the main limiting factor for its detection. This can be done for each data source by visually enhancing the contrast, i.e. the properties of the RGB image representing the data or in changing the display of the data itself. GIS analysis tools are capable of visualizing different aspects of the recorded data in order to optimize the contrast. As already mentioned, for the display of topographical data various properties can be adducted (e.g. slope, openness, view shed) (Doneus 2013b).

For integrated interpretation of different datasets a combination of these data can also be pursued. This can result in either image fusion or data fusion. The latter generates a new dataset out of two or more datasets based on strict mathematical rules. It is applied for merging multisensory information to construct a new dataset – a new impression.[35] If it is applied for spatio-temporal analysis it is also referred to as data integration. It is often used when temporal and spatial data has to be combined to receive an overall view of the situation. In principle a G-AIS is also designed to analyze the basic principles and the mathematical rules to describe the fusion parameters of the available datasets.

For the more specific techniques of image fusion, different filters and summarization operations were applied on two or more images to generate a composite image. This composite image should ideally enhance the visibility and contrast of archaeological features (or other features of concern). Image fusion can be operated on the feature-, signal- and symbolic levels. For the fusion of raster data a pixel-based algorithm approach is most relevant. Recently the METLAB based toolbox TAIFU (**t**oolbox for **a**rchaeological **i**mage **fu**sion) was developed and presented by the LBI ArchPro (Filzwieser 2017). So far composite images generated from GPR and magnetic data proofed the

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[35] The human brain is a perfect data fusion operator in combining different human senses in order to gain a filtered overall impression of the most relevant information.

applicability of TAIFU for enhancing visual information and suppressing interfering parameters. Observed archaeological structures (a house constructed by posts placed in pits, Denmark) became more clearly visible, single features were more distinct. Nevertheless only a single image-biased view of the data guarantees the control of possible interpretations. Within the fusion process important information might become lost. Therefore relying only on composite images cannot be recommended, which can be postulated as the primary rule for using image fusion (Filzwieser 2017). So far the application of TAIFU has only been tested exemplarily. Through the presented results the strong influence of the geological and pedological settings in correlation to the physical properties of the observed features is highlighted. As Filzwieser points out only a limited selection of all fusion algorithms supported by TAIFU has been applied for the image fusion based interpretation. Additionally each algorithm also provides a great variety of settings. The image fusion process was stopped as soon as the composite seemed to be optimized for the individual setting (including subjective experience and physical environment) (Filzwieser 2017).

Visualization of the results

Most recorded data is a projection of physical properties, representing volumetric features, onto a 2D surface. A complete understanding of the observed information can only be derived from 3D reasoning. For supporting this, 3D viewers are crucial for investigating the spatial superposition of archaeological entities. A very simple viewer is provided through ArcScene, which is a 2.5D representation. When surfaces get more complex, viewers capable of a true 3D display are preferable. In general it must be distinguished between 3D objects representing the existing evidence and reconstructed objects. For the latter a 3D display is of great importance in controlling the reliability of the reconstructed objects regarding their extension, position and temporal relation to other objects. As a matter of fact one object can never share the same space with another object at the same (archaeological) time. This very simple rule enables a basic kind of testing function for the plausibility of a suggested spatio-temporal reconstruction. The visualization of these 3D objects together with the basic datasets on which they rely is a basic demand for a subsequent multidisciplinary scientific analysis.

A very simple 3D viewer capable of displaying basic information together with objects is Arch4DInspector, which was developed by the LBI ArchPro. Multiple objects also representing different archaeological phases can be displayed together with basic datasets. The Unity based Arch4DInspector has been primarily designed to also serve as an online tool for the scientific discussion of results and guarantee availability of the data and results. Models derived from G-AIS datasets can be imported and shared. Its straightforward approach allows the argumentation of different solutions for spatio-temporal problems (Wallner et al. 2015).

PAPER #4: The Tell el Daba Archaeological Information System: adding the fourth dimension to legacy datasets of long-term excavations

Preamble

The following paper illustrates the design of an archaeological information system (AIS) based on a geographic information system (GIS). The main aim of the project described in the paper is the development of an optimized digitization, archiving and interpretation workflow of the legacy dataset of Tell el Daba. The GIS-based AIS (G-AIS) introduced for this purpose consists of the main components necessary for a reproducible and integrated archaeological interpretation of multiple datasets. In this specific case the comparability of the legacy dataset with data gained through recent methodology must be guaranteed.

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Abstract

Archaeological research relies on the documentation and analysis of archaeological entities in space and time, i.e. the stratigraphic ordering of these units resulting in a stratigraphic sequence. A GIS-based archaeological Information System (AIS) organizes archaeological entities and associated attributable information according to its specific three-dimensional geographical position based on the framework provided by a Geographical Information System (GIS). To compile a stratigraphic sequence of these entities located in space, the respective GIS-based AIS have to be extended by the fourth dimension – time. The paper presents the according extension of ArcGIS (ESRI) by a stratigraphic sequence composer with integrated interval-based time model, as the basic digital environment for spatio-temporal analysis of archaeological excavation datasets.

The long-term excavation at Tell el-Daba, Egypt was chosen as a case study to evaluate the applicability of respective digital analysis tools using a georeferenced 4D AIS on non-digital and incomplete excavation datasets. As most existing archaeological excavation datasets are based upon long-term inconsistent and analogue data it is crucial to integrate and handle such data to ensure their accessibility for state-of-the-art archaeological spatio-temporal data analysis.

Introduction

Most archaeological datasets rely on legacy data recorded throughout the last decades and even centuries. In fact most archaeological data and information are based on long-term excavations and surveys incorporating inconsistencies due to evolving documentation systems and missing data due to arbitrary excavation. Especially since the introduction of the principles of archaeological stratigraphy in 1979 (Harris 1979) the archaeological methodology has seen basic changes in the paradigm resulting in major developments in the applied documentation techniques and basic theoretical concepts enforced by the advent of Geographical Information Systems (Neubauer 2004).

Considering the fact that archaeological excavation results are always interpretative and depend on the applied methods (Kucera and Löcker 2007)[36] the issue of respective intra-site and inter-site comparability of results based on the various methodological approaches applied becomes prevalent. Especially the aspects of intra-site integration of stratigraphic sequences and their inter-site comparison are of vital importance. In respect to the spatial and temporal properties of every archaeological entity an archaeological information system (AIS) for the organisation, display and analysis has to be GIS-based (Arroyo-Bishop and Lantada Zarzosa 1995) and extended to 4D (Roo et al. 2014).

The digitization of analogue excavation archives is crucial for the comparability with new digital datasets achieved through state-of-the-art methodology (e.g. stratigraphic excavations, digital recording techniques, geoarchaeological and morphological sampling). Redundancy is increased regarding the preservation of the data. To gain comparability and reproducibility of results a standardized workflow for the digitization, interpretation and spatio-temporal analysis of the data is necessary.

It is the aim of the project “A puzzle in 4D” to develop and apply workflows and techniques to digitally preserve, archive and interpret legacy data using the example of the excavations at Tell el-Daba (TD). Furthermore the possibility of reconstructing undocumented and missing information will be examined according to a procedure best described as “reverse excavating”. In reconstructing the

[36] The paper “Reading the past reading the data” is printed in chapter “Discussion”, pp.166, in this thesis.

workflow of the original excavation and translating it into a stratigraphic sequence datasets can be completed and the reliability of given datasets evaluated. Major scientific tasks are the digitization of the TD legacy datasets, metadata and semantic enrichment, the development of strategies for data archiving and open source access according to international standards, the development of a 4D AIS, virtual reconstruction, visualization and dissemination.

The development of a GIS-based 4D AIS will secure comparability of the TD legacy datasets in accordance with stratigraphic theory and methodology, a task, mainly undertaken by the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro). Best routines for every task will be evaluated and standardized. We will show that the AIS will enhance and simplify further archaeological interpretation. Respective results will be reproducible in respect to the confirmability of the origin of the archaeological information.

Within this paper we will present (1) the basic applied principles and rules for the segmentation of space into SU resulting in spatio-temporal relations displayed by a stratigraphic sequence, (2) the basic design and components of a GIS-based 4D AIS recently developed and (3) a first suggestion for a standardized workflow for the digital segmentation and archaeological interpretation optimized for the TD dataset.

The case study Tel el-Daba

TD is located approximately 150 km north-east of Cairo in the fertile Nile-Delta. The site is revealing archaeological evidence from the 12th to 18th dynasties (early second millennium BC) (Bietak 1970, 1975, 1991; Bietak et al. 2007; Bietak 2010; Kopetzky 2010) and was during the 15th dynasty the capital city of the Hyksos. The area of the ancient town covers about 2.5 km^2. Since 1966 excavations were conducted by the Austrian Archaeological Institute (ÖAI) under the direction of Manfred Bietak. Until now around 50 years of active fieldwork campaigns were carried out, resulting in an enormous amount of field protocols, drawings, photographs and prospection survey data (Bietak 1996, 2001, 2013/2014). Excavations of mainly residential buildings, tombs and temples show a wealthy society with contacts to many parts of the eastern Mediterranean including a unique connection to Minoan culture. The site is also well-known for thousands of fragments of Minoan-style wall paintings, which were discovered inside the Egyptian palace complex, depicting e.g. scenes with bulls and bull-leapers. The excavation was carried out with a mixed methodology of excavating in spits biased by observable artificial surfaces such as walls and floors (Aspöck et al. 2015).

Figure 34: Situation at the excavations in TD in 1979. 1m wide bars separate the quadrants (15 x 15m) of area F/I (© OREA/ÖAI archive).

Since the start of the excavation the applied excavation methodology stayed the same to secure consistency of the dataset. However, documentation methodology changed in 1996, with the introduction of the so-called locus system at TD. In many instances a locus corresponds to the definition of a stratigraphic unit, but generally what defines a locus is defined individually at each excavation (Masur et al. 2014). Further changes in the documentation methodology took place as part of technological advances in the field, with increasingly digital documentation methods being used (Aspöck et al. 2015).

Excavations at TD took place in five areas (Ezbet Helmi (H/I-VI), Ezet Rushdi (R/I-IV), Catana (E/I), Tell (A/N+A/I-V), Feld (F/I-II)), which are subdivided into quadratic trenches (squares) of the usual size of 10 x 10 m or 15 x 15m respectively. The squares were separated by bars of 1m width guaranteeing the documentation of cross sections. Each square was excavated in spits resulting in a dataset, which consists mainly of a handwritten record (including sketches), drawings (levels, details and cross sections in the scales 1:50, 1:20, 1:10) and a photographic documentation (B&W, RGB and slides). The main observed archaeological structures have been also interpretatively drawn in a generalized map (ink drawing) and partly digitized with Auto-CAD (Intergraph). During the first campaigns a relative grid was used for positioning, which was geographically referenced and embedded within the global WGS84 coordinate system throughout a geodetic survey in 2008 (Kurtze 2008).

For the development and testing of an AIS, which had to be optimized for the digitization, segmentation and analysis of the TD dataset, a subset of the data was chosen. Area F/I has already been analysed and interpreted archaeologically and allows comparison of the newly gained results with the existing archaeological interpretations.

In the uppermost levels of the area a temple was found dedicated to stratum a/2 (first half of the 15th Dynasty) followed by a villa belonging to stratum b (middle of the 13th to the end of the 12th Dynasty). Due to different utilisation phases of the villa stratum b is subdivided into b/3 to b/1. Within stratum b also offering pits were documented (Müller 2003). At a deeper level the ruin of a huge building, most likely a palace or a villa from stratum c (begin of the 13th to the end of the 12th Dynasty) was found as well as the palace/villa itself, belonging to stratum d/1 (early 13th to late 12th Dynasty) (Eigner 1996). Like the younger villa this building is subdivided into two utilisation phases d/1.1 and d/1.2 and respective tombs (Schiestl 2009). An earlier level yielded the Mittelsaalhaus, belonging to stratum d/2 (early 13th to late 12th Dynasty) covering the workmen village (Czerny 1999) of stratum e, dating to the 12th Dynasty. The mentioned strata are linked to the superordinate Tell el-Daba Phases E/2 down to N/1-3 (Bietak 2013/2014). The temporal model of the described sequence of strata related to archaeological phases was the basis for the subsequent temporal analysis.

Figure 35: Overview of quadrant j/21 (level 3) of area F/I in 1979 (OREA/ÖAI Archive).

For detailed analysis a single trench (square j/21) was chosen representing most types of observed archaeological features and structures. For further analysis several specific levels of 40 additional squares displaying the palace and surrounding infrastructure of strata d/1were added to the subset. The legacy dataset includes analogue data (photographs, slides, cross section drawings, level drawings, detail drawings, field protocols, overview maps, topographical maps) and digital data (CAD technical plans, satellite imaginary, topographical data). All these data were taken in account for developing a standardized digitization and segmentation procedure.[37]

Basic principles of segmentation

The first step within a comprehensive digitization process is to transfer the various data sources, i.e. photographs, maps, sketches, lists, notebooks etc. into appropriate digital formats for further use in the GIS-based archaeological information system (AIS).

[37] The term "digitization" could be firstly used for transferring analogue into digital data. In this case a 1:1 projection of the illustrated information has to be achieved. Secondly it also describes the process of generalizing this information e.g. if a drawing of a pit is reduced to its outline in drawing a polygon around it. This can also be called vectorization of selected parts of the data. If this is the case, the digitization results in the segmentation of an area or space.

The extraction of the relevant stratigraphic units (SU) from analogue or digitized excavation maps is based on digitizing archaeological entities known as stratigraphic units using basic GIS functionality. Every stratigraphic unit (i.e. deposits and surfaces) (Neubauer 2007; Traxler and Neubauer 2008) is characterized by its geographic position and extent. Surfaces are defined by their immaterial topography whereas deposits bear material components (artifacts, composition, texture etc.).

Deposits and surfaces can be described further based on their spatial and temporal relations. From the analysis of the spatial relations, i.e. superposition, a basic stratigraphic sequence according to the principles of archaeological stratigraphy (Harris 1979) is derived. This sequence has to be refined based on the temporal relations of all units. Since every archaeological entity could be defined temporally as a time span or time interval rather than a point in time or event, a temporal analysis of the dataset has to be carried out based on time intervals, advancing the event-based concept of simple temporal relations (earlier, later, contemporary). For this reason interval algebra as suggested by Allen (Allen 1983) has to be introduced as also recently shown by Drap et al. (Drap et al. 2017) As archaeological stratigraphy is based on 4D entities, it deals first of all with the analysis of spatio-temporal relations of archaeological stratigraphic units to derive the formation of the respective stratification. Only spatio-temporal analysis is capable of illustrating the changes of an archaeological site or landscape. For defining temporal relation a physical superposition (spatial component) of SU is not necessary. This approach is similar to the monitoring of various processes, which change the attributes and/or the shape of volumes in time (e.g. earth slides, flooding and mining) (Kurte and Durbha 2016).

GIS-based Archaeological Information System (AIS)

The main focus of the research and development done by the LBI ArchPro was the design and implementation of the different components of a GIS-based AIS. Because of the geographical character of archaeological excavation information the appropriate frame is provided by a GIS. Based on the LBI ArchPro's long-term experience of the application of ArcGIS (ESRI) for the interpretation and analysis of archaeological data, ArcGIS Desktop 10.2 was chosen (also in respect for basic compatibility with other software, which can be included also as an extension). In contrary to CAD software a GIS is also capable of dealing with various types of information (e.g. information based on raster datasets, feature classes but also textual information). It is the most appropriate environment to segment space and correlate the generated areas or volumes with the embedded archaeological information. A GIS provides an enormous set of different spatial analysis and data query tools. It is perfectly suited to analyse and display the spatial superposition of archaeological entities. For the digitization and interpretation of 2D based information (e.g. drawings, photographs and maps) ArcMAP 10.2 was used, whereas for the 3D visualization ArcSCENE 10.2 proofed to be perfectly suited for the TD dataset. Although initially a separate 3D viewer had been developed on the basis of true 3D, the 2.5D representation capabilities of ArcSCENE were sufficient. As the 3D objects were derived from a few cross-sections and level drawings, the reconstructed geometry was very simple and a real 3D viewer not necessary. In contrary datasets based on recent 3D data capturing techniques (e.g. Image Based Modelling (Doneus et al. 2011) and Terrestrial Laser Scanning (Doneus and Neubauer 2006; Neubauer 2007)) bear more complex 3D geometry. A voxel based approach for the archaeological biased segmentation of space and further temporal analysis of geospatial processes is preferable (Jjumba and Dragićević 2016).

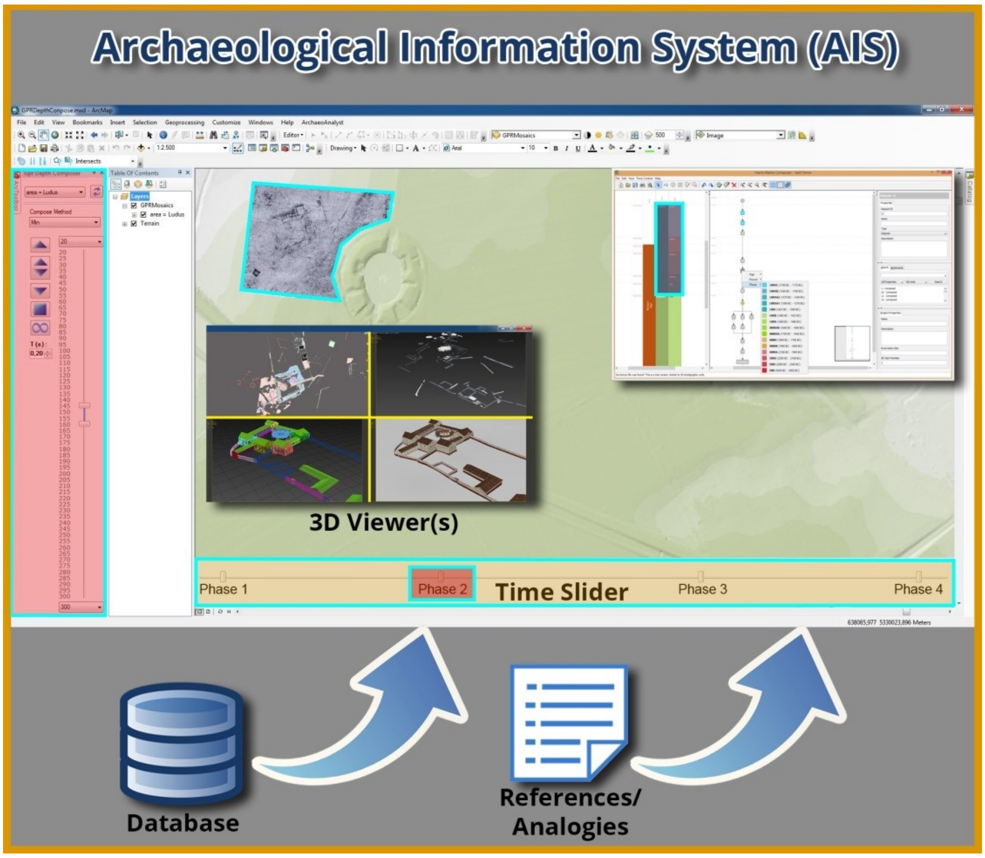

Figure 36: Basic structure of a GIS-based AIS. It combines spatial and temporal information stored in a Geodatabase. Display, analysis and interpretation of the datasets are done within a GIS environment (© LBI ArchPro).

For the temporal interpretation and display of the stratigraphic units a stratigraphic sequencing tool had to be integrated into the AIS. For this purpose the Harris Matrix Composer (HMC) had to be modified according the specific demands of an interval-based temporal interpretation of the data. The first version of the HMC had been developed and released in 2007 (HMC V2.0b) to display the spatial superposition of stratigraphic units (SU).[38] This early version provided the possibility for periodization of groups of SU, but was still missing a consistent temporal model (Traxler and

[38] For further information and to download trial version refer to: http://www.harrismatrixcomposer.com/

Neubauer 2008). To meet this requirement, HMC was modified and an interval-based time model was integrated resulting in HMC+. For a spatio-temporal analysis of the dataset in the AIS the stratigraphic sequencer HMC+ was interfaced to ArcGIS. Currently the functionality is tested and optimized. Whereas it is basically possible to create in each software (ArcGIS and HMC+) new archaeological entities with different identifiers a unique identifier (UID) for each of these entities is necessary. Therefore a hierarchical model of data input has to be defined and optimized for the standardized digitization, segmentation and interpretation workflow. To avoid double naming and contradictions, data input not according to the hierarchical model and standard procedure will be restricted by the AIS.

Depending on the specific demands and possibilities of the digitization workflow, the principal properties of the basic (analogue) datasets, the observed reliability of the datasets and the archiving concept the prototype of a geodatabase (GDB) has been developed. All documented SU will be stored within this ArcGIS GDB and related to all available archaeological information. The GDB will store raster classes (based on drawings, topographical models, aerial imaginary, photographs,…) and feature classes (point, line, polygon) together with respective attributable information to guarantee data queries and to display and correlate specific spatial information with the temporal information stored in HMC+. Once the data is digitized, segmented and embedded, the AIS should be capable of guaranteeing a more efficient study of the documented archaeological information. On this basis an interpretation of the spatio-temporal correlations of SU including concepts of functionality covering large areas could be done and visualized.

Digitization and segmentation

Three tasks for the implementation of the legacy dataset of TD into the proposed AIS can be distinguished. (1) The analogue data has to be digitized. This procedure has to be optimized regarding the most practical resolution for each dataset. (2) The digital data has to be georeferenced for import into the GIS-based AIS. (3) The data has to be segmented digitally according to specified and well-defined rules.

A GIS project was set up according to the geographical coordinate system used in TD since 2008 (Kurtze 2008). All geographic transformations were based on this coordinate system. For a general overview of the area, aerial and satellite imaginary were included, also to secure a fast control of the uploaded and georeferenced data. All drawings (level drawings, cross sections, detail drawings) were scanned, partly assembled in Photoshop and georeferenced in ArcGIS 10.2. Rectification of the drawings was tested, but proved not to be relevant for accuracy.

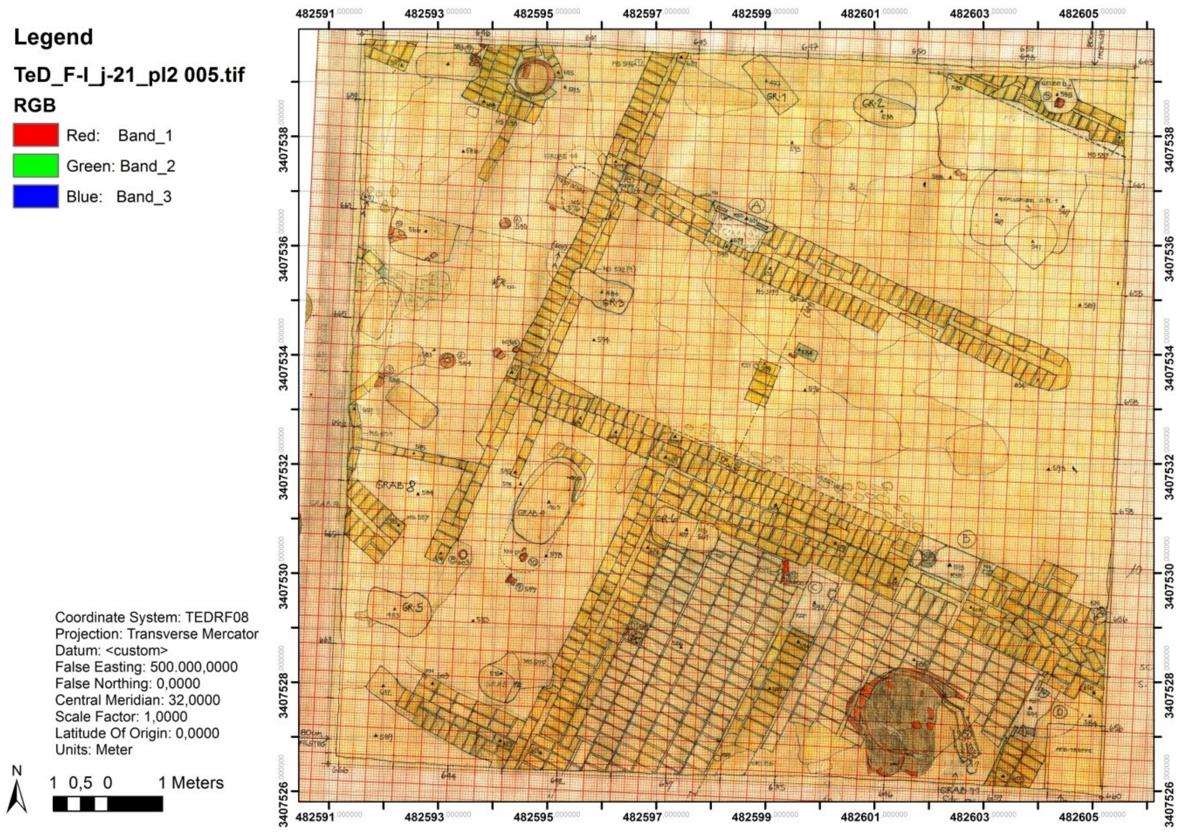

Figure 37: After digitization level drawings in the scale 1:50 are imported and georeferenced for further treatment in GIS. The drawing of level 2 of quadrant j/21 is displayed (©LBI ArchPro).

Most maps were drawn in the scale 1:50, which suggests a resolution dependant on the thickness of the line of a pencil or crayon. Based on this a precision of more than 5cm has to be taken in account, whereas accuracy is more or less personalized. It depends on the recorded situation and who recorded it, but should be expected within the range of approx. 5 to 10cm. For the data of square j/21 it was decided to digitize all features including single bricks, artifacts and bones with polygons. It had been argued, that the digitization of every single brick is an enormous expenditure of time and hardly could be done for the whole area regarding cost and time efficiency. Additionally a single brick within a wall bond is rarely seen as a single SU when being interpreted archaeologically. Nevertheless the analysis of the type, material and location of a brick specifies the functionality and spatial relations of a wall. This information is recorded in the drawings. The question whether to digitize only walls or also bricks is dependent on the expected degree of confirmability and reproducibility of gained archaeological interpretations within a quantitative approach. To investigate the benefits and advantages every approach was evaluated.

The segmentation and vectorization of the data was done in ArcMAP 10.2, resulting in polygons for every observed feature. The extension of the features in z-direction was derived from measured height points from the drawings and educated guessing (e.g. the thickness and size of bricks are more or less comparable). In a first step, all types of analogue but also digital data of one square (j/21) in area F/I have been integrated in the AIS and all features digitised. In a second step, information regarding a specific phase (stratum d/1.1) of the whole area F/I was digitized representing the presumed structures of a palace, surrounding infrastructure and graves mentioned earlier.

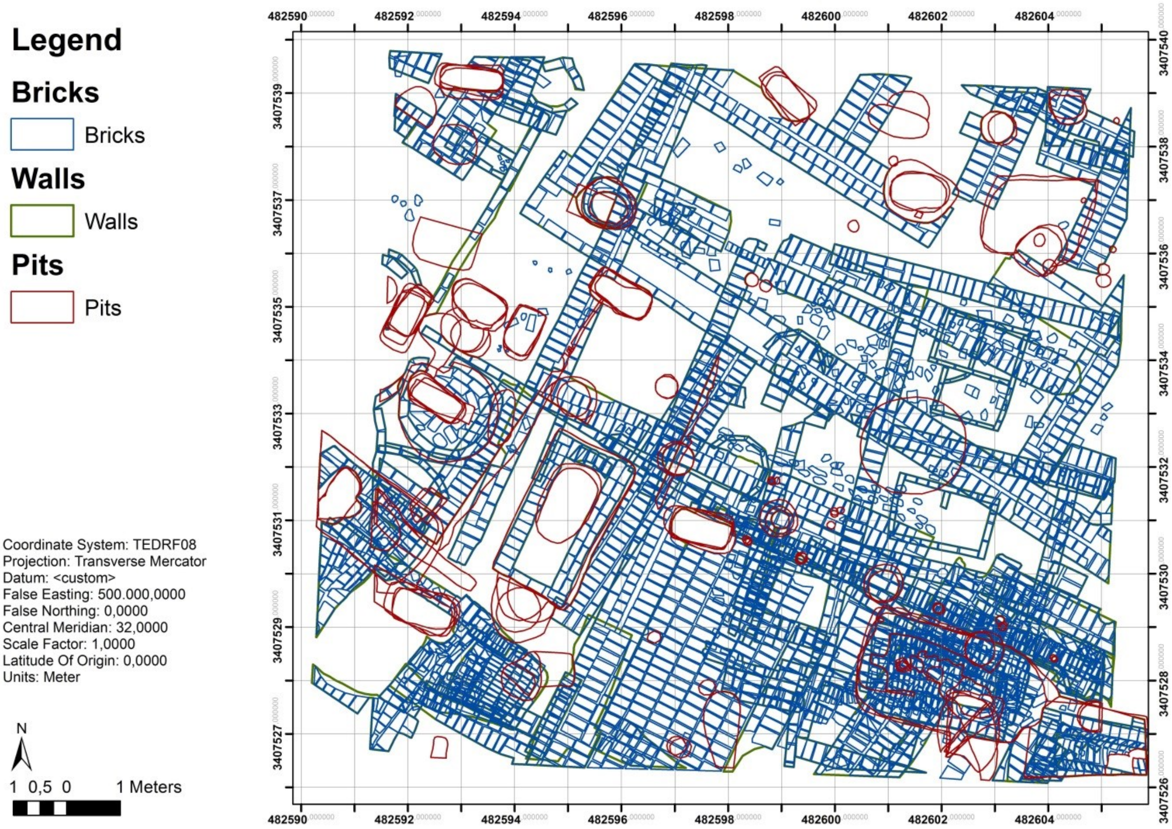

Figure 38: Digitized bricks, walls and pits of all levels of square j/21 (© LBI ArchPro).

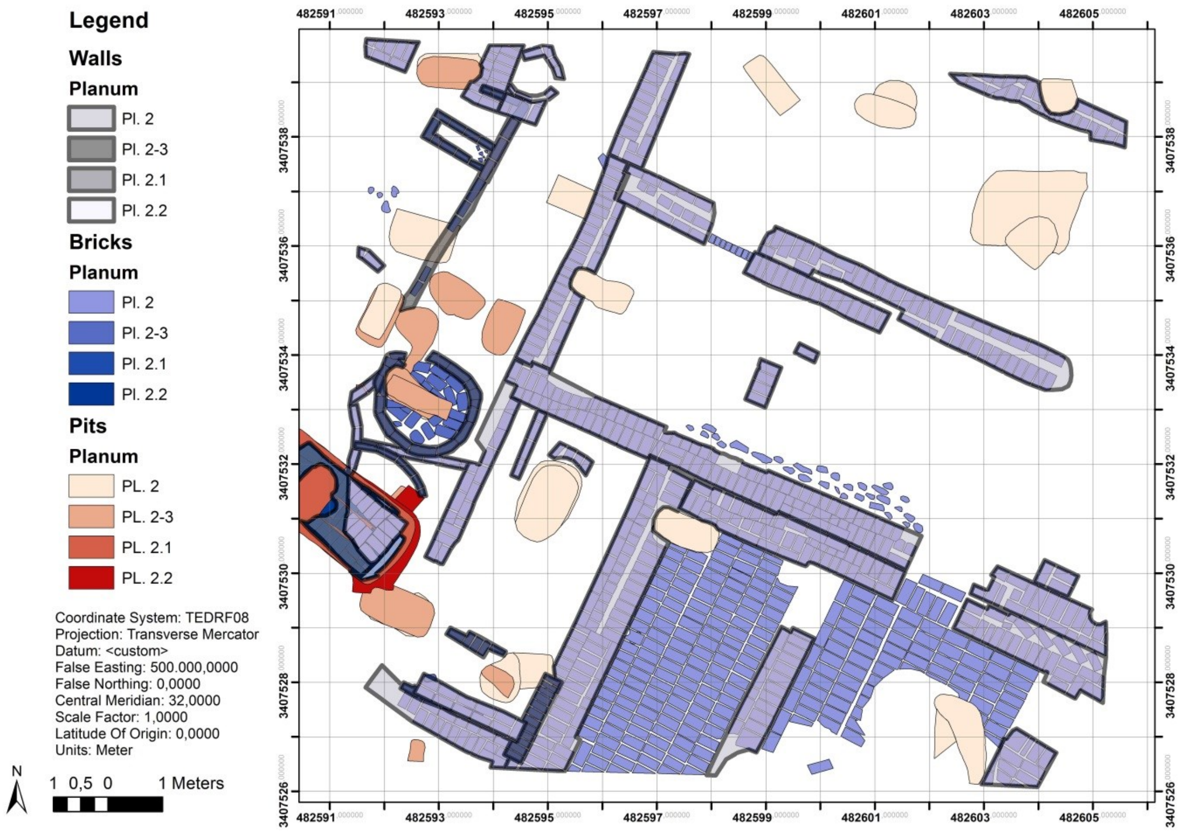

Figure 39: A schematic map of pits, walls and bricks documented on level 2 of j/21 (© LBI ArchPro).

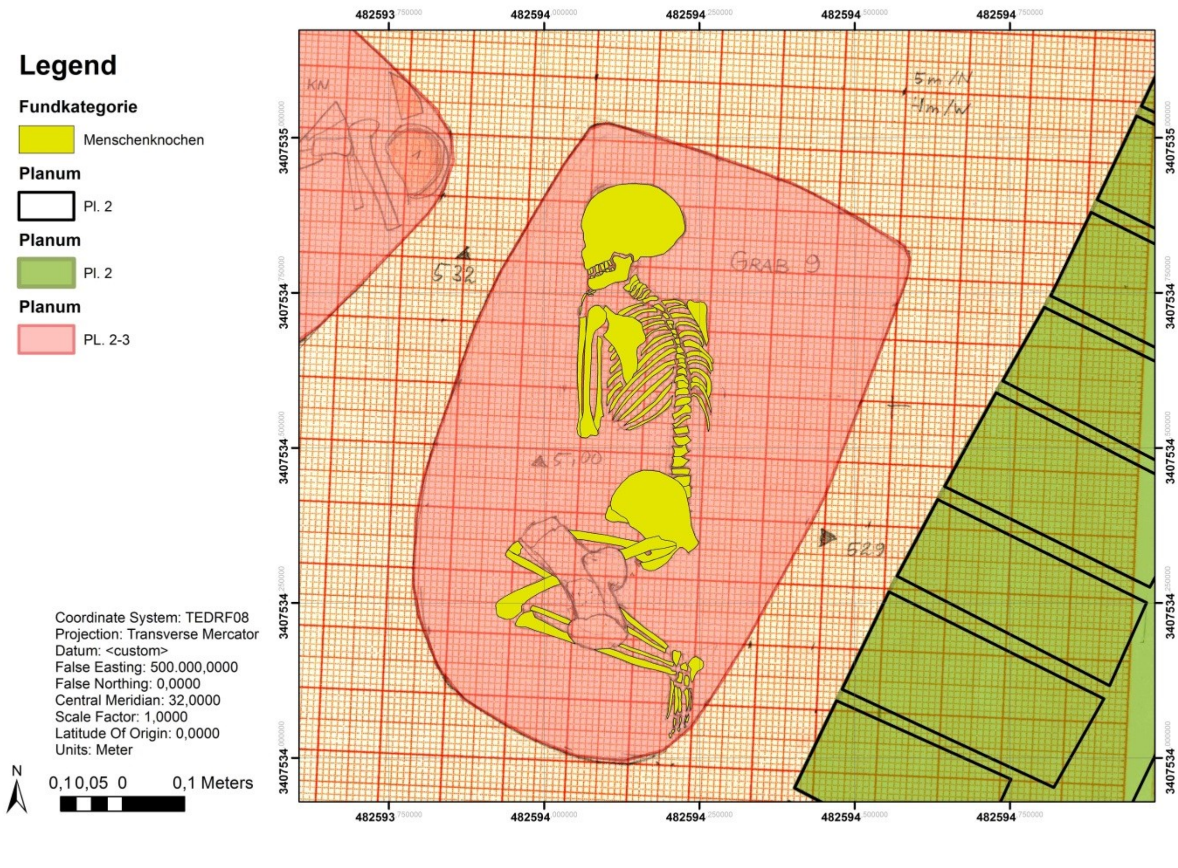

Figure 40: Digitization of a detail drawing. Grave 9 in quadrant j/21 (© LBI ArchPro).

Figure 41: Photograph of grave 9 in quadrant j/21 (© OREA/ÖAI archive).

For the development of a geodatabase (GDB) all information at hand was collected and included within the attribute tables of every feature class. On basis of the collected information data was classified according to thematic separation of different feature classes into walls, pits, layers, bricks, building parts and finds. Additionally, a separate feature class was created to mark the position of the sections. Each attribute table of the different feature classes displays archaeological information about a feature derived from the drawings (e.g. the used color code indicates specific material), the field protocol, cross sections and photographs. Further attributes deal with available metadata (e.g. source, filename or identifiers of documents and archaeological- and excavation objects). One important source of information was the personal communication with the TD researchers at OREA.

The main aim of providing detailed information in these attribute tables is to guarantee reproducibility of archaeological analysis and interpretation of results, as well as preparation of the data for the following archiving process (adding identifiers complying with metadata format developed by OREA). The attribute tables provide the basis for the design of the TD-specific GDB, which will be used to digitise further areas of TD excavations for stratigraphic analysis. So far the digitized data set of square j/21 consists of nearly 4500 recorded features separated into the aforementioned six different feature classes.

For testing and developing the described workflow procedures as a basis for the spatial and temporal expert analysis in a 4D AIS within a larger area another subset of the data was chosen. All data available of a specific archaeological phase was digitized, namely Tell el-Daba phase G/4 (stratum d/1.1), represented by a palace and tombs in area F/I. This subset consists of the data of 40 squares (i/20-23, j/20-23, k/19-23, l/16-21, m/17-20, n/17-21, o/16-21 and p16-21), including square j/21.

All relevant field drawings were collected, scanned, imported and georeferenced in ArcGIS according to the Tell el-Daba coordinate system. In most cases, only one arbitrary level (planum) representing stratum d/1.1 had to be taken in account. Beside that also the general AutoCAD map and a generalized overview map (ink drawing) of the stratum were imported and georeferenced. Based on the previous experiences regarding the digitization of all bricks in square j/21, only the outlines of the walls were vectorised. Arguing that the digitization of every single brick takes a lot of time, it was also a question, whether comparable results could be derived on basis of a reduced digitized dataset.

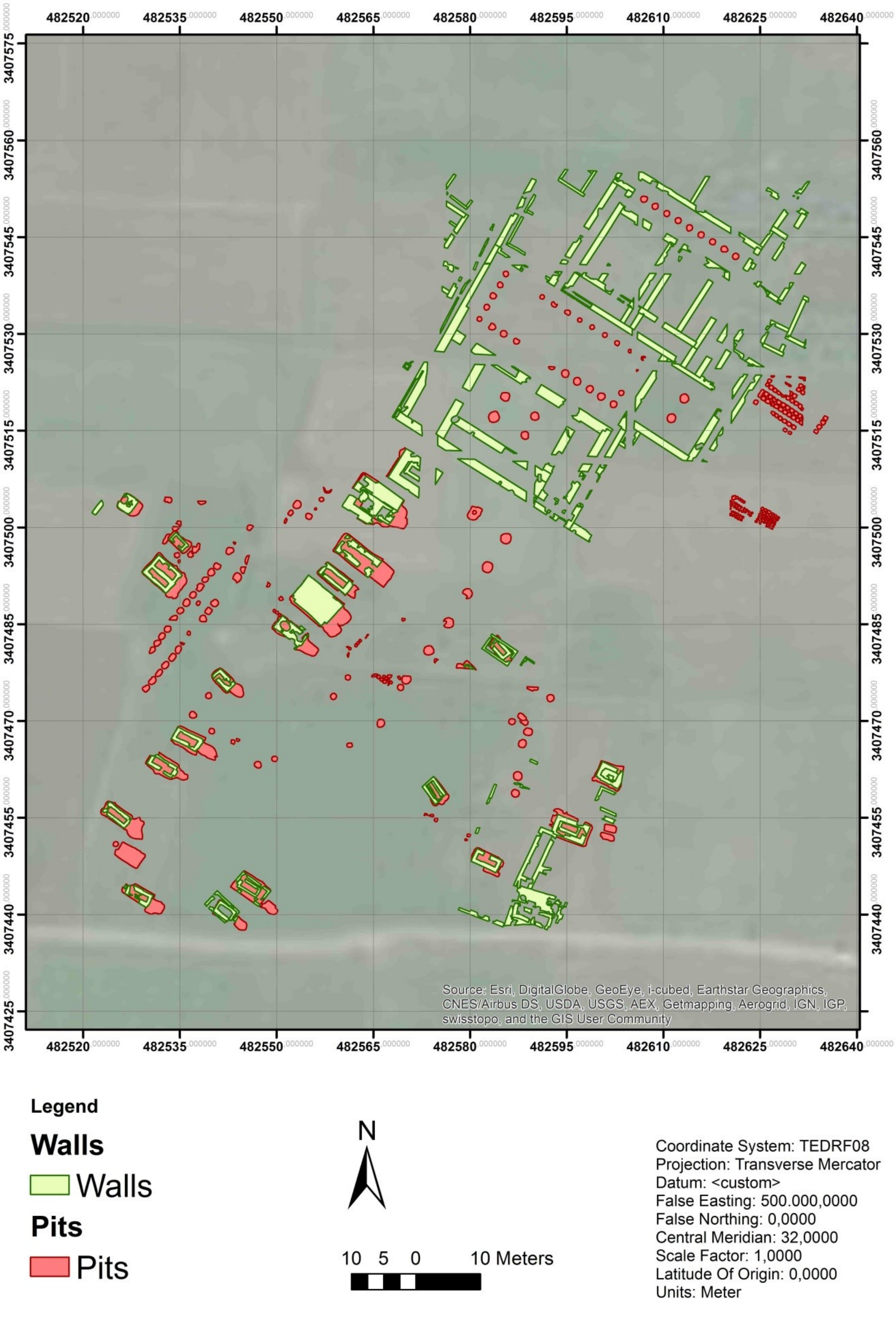

Figure 42: Phase map of stratum d/1.1 displaying pits and walls of the respective quadrants (© LBI ArchPro).

Like for j/21 a GIS database was established, containing more or less the same columns for data and metadata. If available, additional information deducible from cross sections, the handwritten record and from publications was embedded in the database. So far more than 500 features numbered consecutively in respect to the already digitized dataset are listed in the database.

The digitization process, including the recording of heights indicated in the drawings and cross-sections, results in volumetric features. Archaeological information concerning every feature is available throughout the database. Based on these properties the spatial superposition of the observed features can be derived and SUs defined. A stratigraphic sequence of all recorded features has to be done. For this purpose a flexible visualization and display of the single volumetric features is crucial.

Visualization – spatial and temporal relation

Within each feature class of the database of both subsets the attributes extrusion and base height for the volumetric representation are included. They are relevant for the display of the digitized features and structures as volumes in ArcScene 10.2. This depiction mode allows the visualization of entities from different arbitrary documentation levels in 3D at the same time. It is a powerful tool for archaeological interpretation in displaying and visualizing spatial superposition of the recorded 3D volumes resulting in the specification of stratigraphic units (SU). The stratigraphic sequence is generated within the software HMC+.

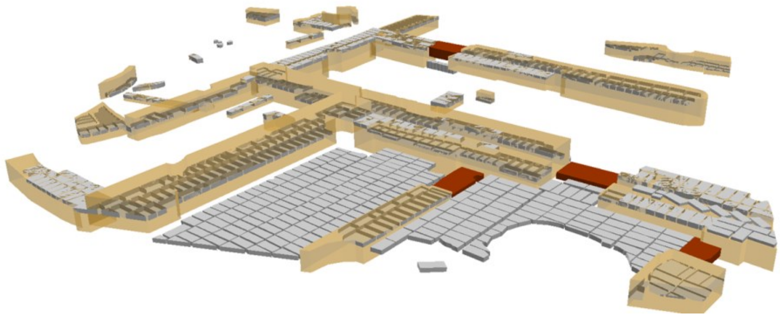

Figure 43: In adding height information indicated in the drawings, structures could be extruded to generate volumetric stratigraphic units. This simple geometry is sufficiently displayed in ArcScene (© LBI ArchPro).

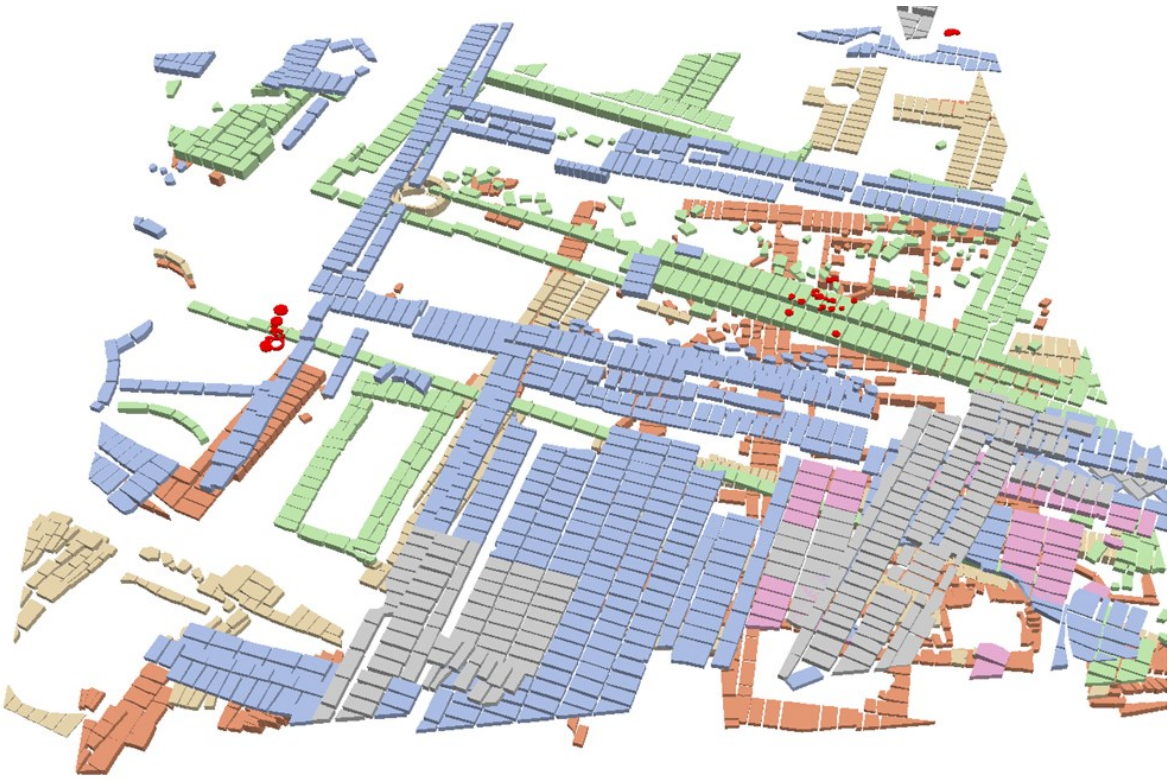

Figure 44: Spatial superposition of bricks belonging to different archaeological phases (© LBI ArchPro).

As a matter of fact a feature might be recorded within several drawings representing always the same SU. In that case it had to be merged into one SU. According to the observed spatial superposition of the digitized features a stratigraphic sequence was generated. The cross sections were used to gain additional information about "missing" SU. As the excavation was carried out in discrete levels of approx. 20cm to 40cm apart, most of the stratigraphic information between these levels had been removed. In this sense the TD dataset is incomplete regarding the loss of surfaces and enclosed volumes due to the selective excavation process. E.g. the infill of a room was removed down to its presumed floor. When a room was artificially separated by the border of the trench or occasionally cut on purpose by an additional cross-section, the archaeological evidence of the stratigraphic sequence lost within these volumes became visible. Parts of lost sequential information could be reconstructed through the analysis of the cross sections (e.g. primary and secondary use and decay of a structure could be observed and represented within a stratigraphic sequence)

For further investigation of spatial relations and to display additional information (e.g. from sections), complex tomb constructions were visualized with the free software SketchUP (Trimble). These detailed reconstructions were made for 3 tombs and a cellar recorded in square j/21. Within SketchUP all drawings (details, side views and sections) can be displayed at the same time according to their geographical position. Based on these drawings 3D models of the specific structures were derived. The surfaces could be textured according the used color code or an idealized more realistic texture respectively, if a more reconstructive style is demanded. Finally each 3D model can be imported into ArcScene for further analysis of the stratigraphic

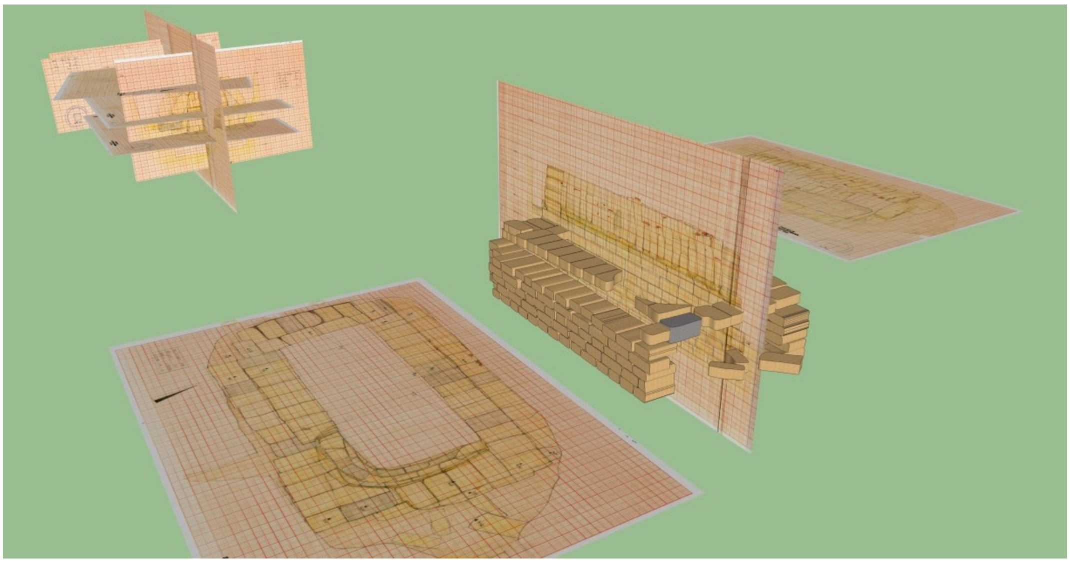

Figure 45: Drawings of cross sections are displayed in SketchUP to reconstruct archaeological structures. Grave 13, quadrant j/21 (© LBI ArchPro).

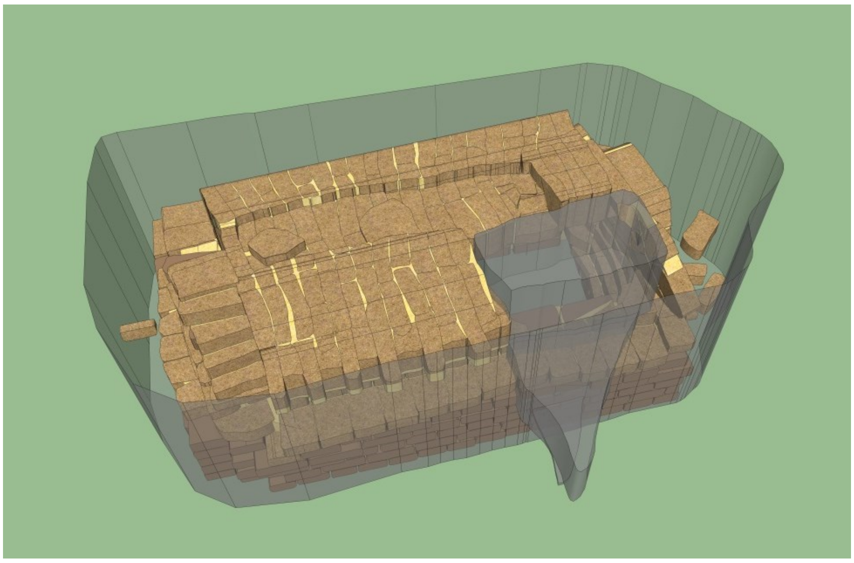

Figure 46: Remodeling of grave 13 in SketchUP (© LBI ArchPro).

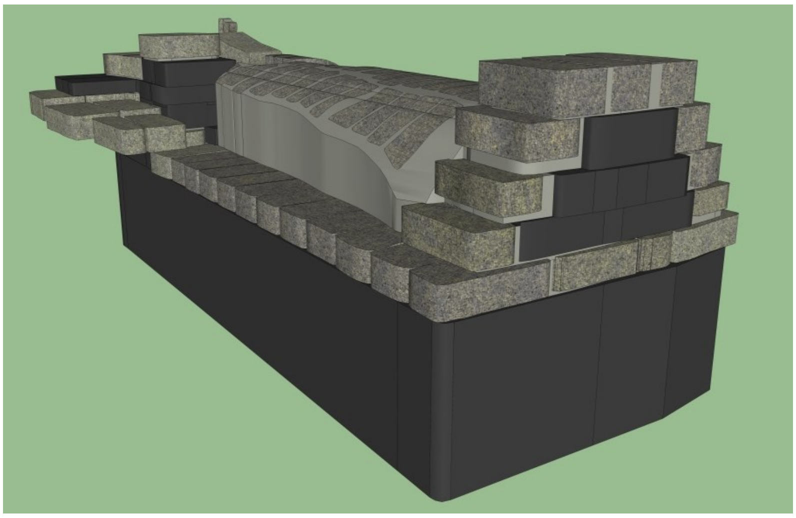

Figure 47: Idealized reconstruction of grave 13 (© LBI ArchPro).

Figure 48: Grave 13 as it was found during the excavations (© OREA/ÖAI Archive).

Once the spatial superposition is represented correctly within the stratigraphic sequence, the temporal attributes of each SU can be set according to the specification of HMC+. Each SU can be either assigned to an archaeological phase or defined by specific start and end dates. It is therefore possible to run a query regarding temporal and spatial attributes. For the further expert-biased archaeological interpretation of functionality, use and decay of the observed features, the display of different assumed phases is extremely helpful. The temporal relations allow displaying features, which are not in direct spatial superposition. This is crucial for the analysis of the relation of different structures spread over a large area (e.g. houses in a settlement).

For a better depiction of archaeological interpretations and reconstructions simple but meaningful software called Arch4DInspector was developed. It basically allows the user to switch between all archaeological data used in the modelling process while observing a reconstructed 3D model on top. The interface consists of buttons that allow the user to enable and disable different types of information which is transparently layered on top of each other, a slider for depicting the 3D model through time and a button that orbits the camera around the data and 3D objects for a better inspection. Suggested reconstructions and spatial and temporal relations of different phases could be displayed online (Torrejon-Valdelomar et al. 2015).

Results

So far more than 5000 archaeological features were digitized in ArcGIS 10.2. During this process several factors were monitored. One of the main issues of the project is to develop a standardized digitization workflow, which is crucial for the complete and redundant digitization and later interpretation of the TD legacy dataset. All necessary individual operations were defined also based on the demanded skills of the person in charge. When aiming to digitize and spatially segment the whole TD dataset this is necessary for effective planning of the project.

A first database was designed, which determines the design of the GDB, which is among the recent tasks of the project and still under development. Data formats, syntax and filenames of feature and raster data have been defined according the archiving routines carried out by OREA.

Several structures were digitized in 3D using SketchUp. The gained 3D objects could illustrate the situation as it was found when it was excavated or an idealized view representing a moment during its use. Whereas the first option could be time consuming, a simple 3D model is mostly sufficient for further proper analysis to generate a stratigraphic sequence. These models could be easily derived within the AIS in extruding the digitized features according their observed height (height points within the drawings stored in the GDB). This is necessary to reconstruct the spatial component of the stratigraphic sequence also within areas, where this information had been lost due to the excavation process. Arch4DInspector proved to be a very handy tool to display basic source information (drawings of levels and cross-sections) together with simple reconstructed volumes to visually control spatial consistency. We have to highlight, that the reconstructed volumes are of hypothetical character.

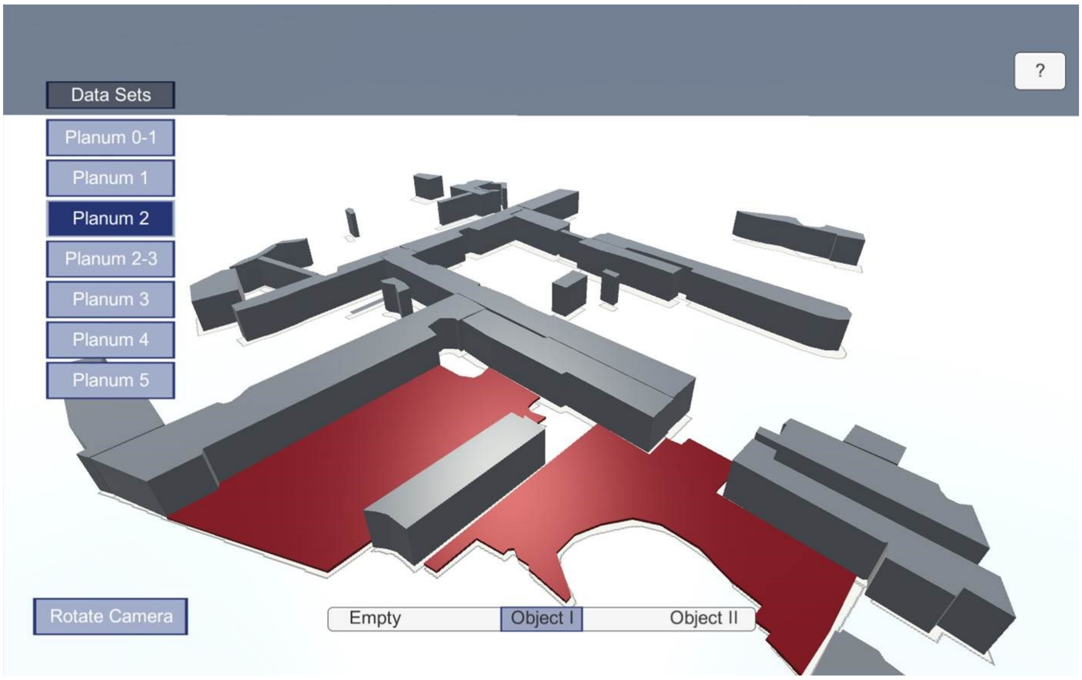

Figure 49: Screenshot of Arch4D. This tool allows displaying 3D models together with additional information (e.g. drawings as base layer). It is also a web-based viewer (© LBI ArchPro).

After the digitization of the selected subsets (namely square j/21 and area F/I), the spatial and temporal superposition was examined and reconstructed leading to a mathematically valid stratigraphic sequence.[39] For this purpose the software HMC+ was renewed and complemented with a temporal model based on time intervals. Based on observations regarding the reconstruction of the incomplete legacy dataset qualitative guessing of the reliability of the various data sources could be derived. The sections proofed to be an important qualitative pool for further information about not defined SU.

The average precision and especially accuracy of the data are not quantifiable. Precision regarding the spatial resolution is related to the scale of the drawings and the recorded situation resulting in an estimated error range of 5 to 10 cm. Contradictions within the legacy dataset (e.g. physically impossible spatial superposition of SU documented in the cross-sections and the level drawings respectively),could be detected through the analysis of the reconstructed stratigraphic sequence.

For the reconstruction of a valid stratigraphic sequence the suggested structure of an AIS (including ArcGIS, HMC+ and a GDB) specified for the demands of the TD project proofed to be very efficient. In

[39] The validation of a stratigraphic sequence is mathematically argued. As the primary stratigraphic information is lost through an archaeological excavation, the stratigraphy represents the observed stratification of the archaeological site and is therefore always interpretative and hypothetical. The hypothetical stratigraphic sequences derived from the spatial and temporal analysis supported by the GIS-based AIS are valid in respect to the laws of stratification.

setting up a GIS-based AIS every item of the digital archive will be specified by its geographical location. It is the basis for further archaeological interpretation of the dataset as well as for a comprehensive virtual reconstruction of the site.

Conclusion

Legacy excavation data are in most cases incomplete compared to recently derived datasets. Regarding the complete description and segmentation of an archaeological stratification, volumes have to be reconstructed, where data are missing. A stratigraphic sequence has to represent the whole excavated archaeological volume i.e. the complete stratification. An AIS strongly enforces the possibilities for remodelling not recorded information. This process can be described as reverse excavating in comparison to the term of reverse engineering, where out of a real model an idealized one is deduced.

In transforming the legacy dataset according to present-day methodology in a standardized and well-documented way the new data and results get comparable with other datasets. Comparability is indeed one of the central demands when analysing data and proposing new archaeological interpretations and theories. These results have to be also reproducible and comprehensive. This is gained within the introduced system by the organization and the correlation of the archaeological information within a GDB. During the digitization of the data and the spatio temporal analysis resulting in a stratigraphic sequence, specific properties displaying the reliability of the different sources have been observed. For example some section drawings were idealized in order to highlight observed correlations. This has to be taken into account when trying to describe and define the accuracy of the digitized data.

The components and specifications of the GIS-based AIS facilitate the analysis and documentation of the spatial and temporal properties of every single SU. Every documented SU is uniquely identified by its geographical location, which also refers to its spatial superposition. Temporal properties of archaeological features, structures and processes are interval based. Allen´s interval algebra mathematically defines the relations of intervals and is therefore perfectly suited for the analysis of respective temporal relations. In this way the description and analysis of spatial and temporal properties allow interpreting archaeological information in 4D.

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PAPER #5: Multi-method archaeological prospection and integrated interpretation investigating the Kreuttal area in Austria

Preamble

The investigation of archaeological landscapes must rely on multiple methodologies derived from different disciplines. The following paper discusses a practical application example of the integrated interpretation of archaeological prospection data. It shall also illustrate the complexity of interfering natural and anthropogenic processes, which determine an archaeological landscape. Another focus is set on the development and testing of motorized magnetometry and the application of further prospection techniques including field walking, airborne and terrestrial laser scanning and soil sampling. Targeted excavations are presented, where the physical and chemical properties of the soils have been exemplarily examined.

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Abstract

Since its foundation in 2010, the Vienna based Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro) has been investigating the area of Kreuttal located 25 km north of Vienna as one of several large-area case studies. In the multifaceted archaeological Kreuttal landscape, covering some 54 km^2, different methods have been tested and developed for efficient large-area archaeological prospection. The case study area is dominated by rolling hills with agriculturally used fields, partly forested. Villages are situated along small creeks. Being situated at a logistically convenient distance from the LBI ArchPro headquarters, the area is well suited to test and improve various methods for archaeological prospection and the subsequent integrated data interpretation. Applied methods include geophysical prospection, airborne and terrestrial laserscanning, aerial photography, soil sampling, field walking and targeted archaeological excavations. A special focus was placed on the development and application of large-area motorized

magnetic prospection. Over the past seven years considerable parts of the landscape have been surveyed and as well investigated using field walking, allowing for the documentation of recent changes. This case study highlights how the acquired datasets provide valuable information on various parameters of fundamental archaeological interest. Soil erosion and accumulation have in the past transformed the landscape significantly, affecting the detection and identification of archaeological remains. By comparing all collected datasets it becomes possible to analyse the various physical parameters, such as topography, soil characteristics and humidity, deriving at integrative data interpretation approach.

Introduction

In order to be able to understand the development of archaeological landscapes through time, the investigation approach has to integrate information derived at multiple scales with differing resolutions. Traditional, spatially limited archaeological excavations accompanied with various analyses of artefacts, biofacts and ecofacts, can provide deep and detailed insights, but only concerning rather small areas. Therefore, these investigations merely allow for a highly focused, therefore biased illumination, and subsequent interpretation of an archaeological site, often missing the context of the surrounding archaeological landscape. This very context is of fundamental importance for the understanding of the development, history and prehistory of any landscape. Landscape archaeology aims to investigate the cultural and natural development across large areas and long periods of time. It focuses on the interactions of human societies with their surrounding environment. For this purpose, the past landscape is examined using various methods based in different scientific disciplines. Once environmental settings have been derived or reconstructed, archaeological theories regarding past societies, their development, as well as their impact on, and dependency of the environment can be studied. Recent methodological developments for integrated interpretation of multidisciplinary data acquired across large areas can provide archaeological and ecological contexts for spatio-temporal analysis at the scale of landscapes.

By investigating the archaeological landscape in a top down approach, from the largest extent to smaller regions and subsequently the site level, detailed phenomena can be observed and analysed following in a deductive sense. For the investigation of the principle structural elements of a landscape, large-area archaeological prospection methods can under suitable conditions reveal patterns of human activity, paleo-environmental settings and their topographical correlation. Different archaeological prospection methods respond differently to environmental conditions and comprise inherent characteristics concerning the mapped physical parameters, sample spacing, measurement sensitivity and speed. The most effective application of any of these methods requires a well-defined research question based on a preliminary analysis of the prevalent physical properties (e.g. geological and pedological background, soil conditions, vegetation, topography), in order to guarantee a certain quality and reproducibility of the acquired data and subsequently deducted results. An integrated interpretational approach may permit the extraction of valuable information, even when evidence of buried archaeology is not visible in all datasets.

Among the methods considered for large-area archaeological prospection is aerial photography, airborne laser scanning (ALS) and near-surface geophysical prospection. For over a century, aerial photography has been the primary and most accepted source for the investigation of archaeological landscapes. This method may permit the efficient coverage of large areas, which has resulted in the discovery and mapping of numerous archaeological sites respectively phenomena throughout the world.[40] However, the detection capability of the aerial photography method is dependent on seasonal changes, weather conditions, vegetation, and geological and pedological settings. Over the past decade, airborne laser scanning has been introduced as a promising archaeological prospection technique mapping the topography in great detail. ALS can efficiently be used for the generation of high-resolution digital surface models (DSM), and digital terrain models (DTM) after subsequent vegetation filtering of the data (Doneus and Briese 2006). Therefore, for the past 15 years ALS has been an important source for the detection of topographically distinguishable archaeological features, with particular success in forested areas (Doneus et al. 2008).

Ground based near-surface geophysical prospection methods have for the last sixty years successfully been applied for archaeological purposes. Namely magnetic prospection, ground-penetrating radar (GPR), magnetic susceptibility measurement, earth resistance and electromagnetic induction measurements have been adapted for archaeological prospection purposes. The exact positioning of the geophysical prospection data is fundamental for the correct alignment and mapping of the collected data that may image buried archaeological features, which expressed in the prospection data are commonly referred to as “anomalies” (Neubauer 2001; Aspinall et al. 2009). Traditionally, for the purpose of performing a ground based prospection survey, usually a grid had to be established and the measurement devices were operated manually along defined survey lines or measurements transects. The potential for dense sample spacing and spatial coverage was rather limited in the early days, but improved steadily. For the application of geophysical prospection at the scale of landscapes it became obvious that a motorization of multi-sensor arrays and the use of automatic positioning systems were required.

[40] We prefer to refer to “archaeological phenomena” rather than to “archaeological sites”. The term “site” implicates an undefined spatial extent of an archaeological entity. In analyzing archaeological landscapes, the necessity arises to segment the investigated area according to different use and functionality. For instance, the buried remains of a prehistoric farmstead might be correlated with a “site”, but it is mostly difficult to define its spatial limitation without knowledge of the yet hidden stratification.

Nowadays, landscape archaeology can rely on various highly efficient archaeological prospection techniques, permitting the coverage of many square kilometers rather than square meters or hectares, in manageable time-frames (Doneus et al. 2007). Within an integrated interpretation approach the results of the acquired large-area, high-resolution datasets can be combined with further archaeological evidence and information based on traditional sources, such as for instance archaeological excavations or historical maps. Using prospection data targeted excavations can be conducted in response to a specific research question, formulated through the multidisciplinary analysis of the archaeological prospection data. Thus, excavations can be used to not only reveal archaeological content of interest, but also to evaluate and optimize the interpretations of the non-destructive prospection surveys.

Within this paper we exemplarily present

- the application of a range of archaeological prospection techniques applied within the large-area case study Kreuttal in Austria, with a special focus on the development of motorized magnetic prospection devices,
- the integrated interpretation of the results within a suggested optimized framework and workflow, and
- the cause of interfering parameters regarding the traceability of features within different datasets.

Archaeological prospection on a landscape scale: case study Kreuttal

Since 2011, the LBI ArchPro investigates the archaeological landscape of the Kreuttal region, located some 30 km northwest of Vienna. A ridge of rolling hills oriented in north-south direction forms a natural barrier to the Marchfeld plains in the east, and marks the boundary to the bay of Korneuburg to the west. This ridge is intersected by a valley – the so called "Kreuttal" – connecting the bay of Korneuburg with the eastern plains. Due to the periglacial deposition of fertile loess soil and its topography, the area is and has been perfectly suited for agriculture. From the top of the ridge, under clear weather conditions the Hungarian plains and the Carpathian Mountains can be seen to the east, and the Alps to the south. The area hosts several large prehistoric settlements, some of which had been fortified, as well as ritual monuments dating from the Neolithic to modern times. This fact also reflects the strategic importance due to the area´s geographical location even in very recent times at the end of World War II. Being at close distance to the LBI ArchPro's headquarters, different archaeological prospection techniques could easily be tested there.

The Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro) was founded in 2010 in Vienna – Austria, with the aim to develop and apply latest methodology and technology for large-area high resolution archaeological prospection. In collaboration with its European partner organizations – universities, museums, national heritage boards, research institutions, regional governmental organizations and small and medium enterprises, the institute conducts several archaeological prospection case studies throughout Europe. Every case study represents a specific archaeological and environmental setting for the development and testing of methodologies and technologies advanced by the institute. Therefore, throughout the past seven years a multi-methodological dataset was created, comprising results from remote sensing (aerial archaeology, airborne laser scanning, imaging spectroscopy), near-surface geophysical prospection (magnetometry, ground-penetrating radar and magnetic susceptibility surveys), geoarchaeological sampling, and field walking. In collaboration with the Vienna Institute for Archaeological Sciences (VIAS) and the Institute of Prehistoric and Historical Archaeology of the University of Vienna, several archaeological excavations within the study area were conducted, based on the non-invasively obtained archaeological prospection results. All of the gathered data was integrated for a complete archaeological interpretation of the prehistoric landscape.

Methodology

General aspects

For the non-invasive investigation of archaeological landscapes a set of well-defined methods is applied in order to solve one or more specific research questions. These questions could either concern research into further methodological development and technological advancement, or archaeological research. Since the generated results will always depend on the chosen methodology, a clear definition of the purposes and limits of every applied method or technique has to be the basis of an integrated interpretational approach. Results and data provided by each individual method have to be compared within a reproducible framework. The development and design of such an integrative methodological and theoretical environment is a scientific challenge. This task includes as well the definition of type and structure of a corresponding database, the appropriate visualization of the data, and its integrative analysis and interpretation.

The main methods used for large-scale high-resolution archaeological prospection in the Kreuttal case study will be briefly described below. They include non- or minimum-invasive methods (mainly the aforementioned prospection techniques) as well as invasive methods (systematic field walking, soil sampling and archaeological excavations). The methodological development of large-scale motorized geophysical prospection (primarily magnetic prospection), which has also been correlation with the analysis of the soil characteristics, was of main interest and will be described in greater detail.

Design of a GIS-based archaeological information system (G-AIS)

Archaeological research always must deal with both legacy datasets and datasets recently recorded. The challenging task herby is to guarantee comparability of these datasets. Older datasets often have to be adapted to be used within a new methodological framework. In this context the reliability of legacy data and their comparability with recent data and results have to be argued carefully. All archaeological data have in common that in principle they can be correlated with a corresponding geographic position and a time interval. Therefore, any archaeological information system (AIS) has to be capable of dealing with spatial and temporal information. This requirement demands the introduction of a 4D AIS as also proposed and described by Roo et al. (Roo et al. 2014), in contrast to common 3D Geographical Information Systems. A typical standard procedure for the interpretation of archaeological prospection data would start with spatial data segmentation, a process that partly can be automated. As second step, data classification of the generated segments is implemented by making use of additional archaeological information. Finally, the generated archaeological entities are correlated with time intervals, ideally resulting in their interpretation regarding their function and spatial as well as temporal extension.

We want to stress that important archaeological information can already be derived through the simple comparison of different datasets (e.g. aerial imaginary and geophysical prospection data). In this respect, the application of an integrated interpretation approach is self-evident. As archaeology traditionally draws on analogies (and the above mentioned comparison is just one), the comparison of prospection data sets in order to reveal pattern and analogies, fits perfectly into this archaeological method of operation. Nevertheless, mostly arguments are based on qualitative analysis of the data rather than a quantitative analysis as made possible through the use of a 3D or 4D AIS. The design of such an AIS should guarantee the reproducibility and comparability of presented results in a quantitative manner.

For this purpose, a GIS-based archaeological information system (G-AIS) was especially designed to deal with archaeological prospection data and their integrated spatial[41] interpretation. This G-AIS basically consists of a GIS core, permitting the control and analysis of spatial relations, and a dedicated geodatabase, which includes raster datasets and feature classes (point, line and polygon). For the integrated interpretation of archaeological prospection data, a standardized workflow was developed, starting with the segmentation and classification of the observed archaeological evidence at four levels: features, structures, distinct areas, and seamless areas (Kastowsky-Priglinger 2013).

[41] Within this paper we want to focus on the spatial integrated interpretation, since the causes for presence or absence of specific features within different datasets should be discussed. This discussion is more likely to be linked to spatial concepts and material aspects.

The basic level is the single archaeological feature (e.g. remains of pits, postholes, walls, etc.) followed by structures (e.g. house). Whereas data segmentation on the first level can partly be semi-automated in case of magnetic prospection data, all other steps have to be carried out manually. The next two levels (distinct areas and seamless areas), represent more of an abstract functionality of the defined entities. For example, a farmstead is a distinct area consisting of features and structures. Its spatial extension is related to the functionality of this area; its boundaries possibly can also be interpreted on the basis of other datasets.

The comparison and integrated interpretation of multiple datasets are made possible by the G-AIS. For the creation of a suitable raster geodatabase, and as a support for the visualization of in particular geophysical prospection data and their semi-automated interpretation, software tools were developed to be used as extensions of ArcGIS (Torrejón Valdelomar et al. 2016; Pregesbauer et al. 2013).

Within the LBI ArchPro's case study Kreuttal, an integrated mix of methods for data acquisition and data interpretation, including also not archaeologically targeted datasets and legacy data, was developed and applied. At first, all existing data, including geophysical survey data, aerial imagery, airborne laser scanning (ALS) data and airborne imaging spectroscopy data, geological maps, historical maps and field survey data, were collected, digitized (if necessary) and archived. The resulting data archive is the main repository for the raster geodatabase that constantly is being complemented with newly collected data.

Data visualization, integrated interpretation and analysis of all the above listed data are realized within the G-AIS. The spatial database concept of ArcGIS was used for the integrated interpretation of the multiple data sources, utilizing its various possibilities for data visualization. For instance, for the landscape analysis of the topographical information, which is mainly based on ALS data, different visualizations are generated according to various parameters and algorithms that have been developed and successfully applied over the past years. Whereas the processing and visualization of digital terrain models (DTM) according to slope and aspect have been widely applied for the last two decades (Bennett et al. 2012), principle component analysis of shaded relief models (Devereux et al. 2008), local relief modelling (Hesse 2010), and positive and negative openness (Doneus 2013b) provided new improved ways to visualize the data. The mathematical functionality of GIS regarding spatial analysis and network analysis is crucial for the interpretation of the data at the scale of archaeological landscapes. Least cost path analysis allows for the investigation of probable and observed road and path way systems (Doneus 2013a; Gustas and Supernant 2017). In combination with historical maps, it becomes possible to detect previously unknown archaeological sites and to derive the functional segmentation of the archaeological or historical landscape.

On-site visits

Since 2011 various airborne and terrestrial surveys were carried out in the Kreuttal by the LBI ArchPro and its partners, to supplement legacy datasets. Right from the start of the project, the case study team has spent a lot of time walking the case study area in order to visit archaeological structures and to get a feeling for the topographical and spatial relations. Although spatial analysis can be done remotely on a computer in a laboratory, a closer understanding of an archaeological landscape in order to prove or falsify hypotheses[42] can only be gained from experiencing the local topography and contained features by field walking. Additionally, the processes, which transformed evidence of human activity, may still be observable within the landscape. In this sense, the landscape can be regarded as a laboratory at scale 1:1. By way of example, after a heavy thunderstorm in May 2012, one of the major roads was flooded and a large amount of eroded loess soil was deposited on the road. The material originated from a gentle slope uphill. This process illustrated how large masses may be relocated during a single extreme weather event. The deposit, formed within a couple of minutes, was up to 30 cm thick and covered and area of approximately 1,000 m^2, including parts of the mentioned road. At another place, reeds were observed within a cornfield, indicating a swampy zone, suggesting even the presence of a small pond. When the field was spotted during a drier period, this marshy zone was not observable anymore. Observations like these can be very helpful for the archaeological interpretation of landscapes.

Figure 50: The fortification of the "Türkenschanze". Low sun and snow cover reveal topographical details (© M.Kucera).

[42] In this context, as well as in any other, the term "ground truthing" has to be strictly avoided, because it suggests the concept of truth. Regarding the theory of science, truth is neither a valid concept when dealing with hypotheses (Pietschmann, 1996), nor is an invasive archaeological excavation able to verify or falsify geophysical measurements of magnetic permeability, magnetic susceptibility, electric conductivity or dielectric permittivity (Löcker et al. 2015).

Another important aspect of field visits is that one is exposed to the weather. In combination with micro-topographical changes that may reveal favorable places for human occupation and activity, this aspect forms another important source of information by describing micro climatic regions. The preference for a specific location depends on various factors including geographical, social, infra structural and also ritual aspects and must be expected to be multifaceted. Nevertheless first arguments can be derived from geographical description and analysis of the landscape. A Linearbandkeramik (LBK) settlement discovered in the vicinity of the modern village of Hornsburg perfectly illustrates this geographically aspect. The settlement is situated on a shoulder of a slope facing southeast, within a small basin at the end of a valley oriented southwards. The settlement had been protected from the often strong westerly winds, and being located at a fair distance from the bottom of the valley the settled areas avoided the marshy zones. Whereas one Middle Neolithic circular ditch system (Kreisgrabenanlage – KGA) with two ditches and two entrance gateways is located more or less within the settlement area, another one consisting of three ditches and two entrance gateways is located on the top of the opposite ridge of the basin. The latter is completely exposed to the wind, but also must have formed a landmark visible from many other places in the wider area. The second KGA lacks evidence of any larger nearby settlement structures. Both sites were partly excavated in recent years. During these excavations, various processes of soil accumulation and erosion were observed, which have been correlated with the local topography. These observations highlight again the necessity and usefulness of topographical landscape models.

Systematic field walking

From 2012 to 2015 several field walking surveys have been carried out in collaboration with the University of Vienna in the Kreuttal region, during which an area of in total 75 hectare was examined testing also novel data acquisition techniques (Coolen et al. 2013). In general, these surveys should provide the necessary temporal information based on collected material and artefacts. Most of the area was covered with line walking surveys using 5 to 15 m cross-line spacing. On the basis of the geophysical dataset, specific areas have been additionally investigated with raster field walking surveys and individual artefact location by GNSS measurements. This research was driven by the question, whether or not a correlation between the distribution of artefacts found on the surface and the mapped magnetic anomalies can be observed. Of special interest was the spreading of presumed activity zones due to effects of erosion and ploughing, as well as the presence of archaeological material on the surface. The absence of anthropogenic finds on top or in the vicinity of observed magnetic anomalies may indicate their non-anthropogenic origin, or their state of preservation. This argumentation can also be based on the analysis of the local topography.

Aerial archaeology

Since the second half of the 20th century, the Austrian air force has repeatedly undertaken photographic aerial surveys. From the late 1970s, the area of Kreuttal was recorded several times from the air, thereby documenting the recent changes in the landscape. Aerial photographs taken by the Royal Airforce (RAF) in 1943 are also available. Some of these pictures were also used to generate historical digital terrain models (hDTM) applying image based modelling (IBM) techniques (Sevara 2016). Besides the targeted photographic recording of the area for military purposes, several flight missions were undertaken by the Aerial Archive of the Department of Prehistoric and Historical Archaeologyof the University of Vienna over the course of the project. Known archaeological sites were recorded under different environmental and climatic conditions and several new, so far unknown structures of archaeological interest were discovered.

Aerial archaeology has lately seen mayor developments regarding the application of various photographic sensors and filters, as well as automated positioning and orientation equipment (GNSS receivers and Inertial Measurement Units). Recently formulated, standardized workflows were suggested for optimized data capturing, data processing and archiving (Verhoeven and Sevara 2016). An automated workflow for fast and accurate image rectification and geolocation of aerial photographs was developed (Doneus et al. 2016; Verhoeven et al. 2012).

The use of different sensors and the possibilities provided by IBM approaches have widened the range of applications of aerial archaeology. The dataset available for the Kreuttal case study enables the analysis of the landscape regarding different forms of land use and infrastructural changes (e.g. regarding the shift of field borders, the erection of power lines, different agricultural field uses, etc.). DTMs and hDTMs generated with temporally different sets of aerial photographs using IBM allow for the investigation of topographic changes that have occurred over the past 70 years.

Topographic surveys

Digital terrain models based on ALS data were provided by the federal state of Lower Austria. ALS-based topographic data is perfectly suited to detect archaeological and palaeoenvironmental features based on their expression in today's (micro-) relief, even if this impact is very small. The fact that minute features in the relief can even be detected by processing ALS data acquired over vegetated areas has revolutionized our knowledge about archaeological remains preserved in woodlands (Doneus 2013a). A wide range of archaeological and palaeoenvironmental features can be discerned using various visualization techniques (e.g. using color scales based on slope, the local-relief model, positive and negative openness, or multiple hill-shade techniques). Abundant information can be generated on remains of ramparts, mounds, ditches, field systems, terraces, platforms, ruined walls, stone quarries, extraction pits, military hideouts, bomb craters, as well as complete systems of paths and hollow-ways, which become more or less clearly visible within the ALS-based DTM data after digital removal of the vegetation. During the field walking campaigns in the Kreuttal region, such structures were visited and further examined on the ground. Although the 0.5 m resolution of the ALS-based DTM is sufficient for archaeological prospection, higher resolution datasets were desirable for the detailed interpretation of specific locations. In such cases, terrestrial laser scanning (TLS) was applied to generate even more detailed DTMs. Amongst others, the southern entrance gate of the enormous fortified hillfort "Türkenschanze" in Kreuttal was scanned with TLS.

Geophysical prospection

For the cost- and time-efficient large-scale high-resolution geophysical prospection of archaeological landscapes, a motorization of the survey devices, accompanied by precise automatized geospatial positioning based on GNSS technology, has been necessary. The survey systems employed are required to be durable, weather-proofed and easily transportable. Their physical properties and geometrical setup have to permit the collection of data of comparable quality to data collected with traditional manually operated systems. The geophysical sensors have to be moved as smoothly as possible over the survey areas, and measurement and vehicle speed have to be optimized regarding the senor sampling rate. Devices designed for magnetic prospection have to be as much as possible void of magnetically disturbing components (i.e. metal parts or electrically conducting components), without decreasing the mechanical stability of the system. As an entirely non-magnetic motorized prospection system is not realizable, the development and application of data post-processing and filtering procedures mitigating disturbances in the data caused by the measurement system has been crucial. A well-designed geometry of the sensor arrays and carriers, their straight forward maintenance as well as practical fieldwork routines have been elaborated. Given the fact that the case study area is only a short distance by car away from the headquarters of the LBI ArchPro, most of the systems, which have been developed and continuously improved by the LBI ArchPro, were tested in the Kreuttal area. Besides the testing of the physical setup of the systems, general survey logistics and routines were tried and developed. From the experiences made in the Kreuttal case study, clear personal responsibilities, maintenance procedures and survey routines were derived. It was also here, that many of the institute's staff and interns have been trained in the operation of the geophysical survey systems for the first time.

Due to the specific geological and pedological settings in the case study area of Kreuttal, which is characterized by an accumulation of loess, large density variations within the near surface soil layers were not to be expected. Therefore, a main focus was set on the magnetic prospection method.

Ground-penetrating radar (GPR) surveys were only carried out at a smaller scale, namely in areas were erosion was expected to have taken place and the absorbing loess cover has been removed prior to human activity. The average size of the agricultural fields in the investigation area is about three to five hectares, with a topography suited for motorized surveys. First surveys were carried out in the northern part of the case study area, in the vicinity of the villages of Hornsburg and Kreuzstetten.

During the first fieldwork campaigns in 2011, motorized fluxgate magnetometer systems were tested and modified. At this time, these systems had been in operation with minor changes made to their configuration (regarding geometry and type of data loggers), since the first surveys had been carried out by the LBI ArchPro in Stonehenge, Sweden and Norway in summer and autumn of 2010.

In general, a motorized system for magnetic archaeological prospection consists of a non-magnetic cart towed by an all-terrain-vehicle (ATV). At first two slightly different designs of these carts were tested, one with a single drawbar of 6 m length, and the other with a triangular drawbar arrangement. In order to increase transportability and stability, the single drawbar cart was favored and equipped with a telescopic drawbar. This shortened the length of the system during transport to 3 m and allowed for fast deployment of the cart in the field. Most construction parts of the magnetometer sensor cart are made out of fiberglass that are glued or connected with plastic screws.

Figure 51: Motorized magnetic prospection. The multi-sensor array is towed by an ATV (© M.Kucera).

The cart supports up to ten fluxgate gradiometer sensors at a fair distance of about 6 m from the ATV, and is designed to absorb vibrations and bumps with four independently suspended wheels. The cart's suspension is realized through elastic ropes. The tension of these ropes can be adjusted according to the roughness of the surface of the survey area. The wheels are mounted with ballbearings using glass balls, which proved to endure speeds of approx. 50 km/h. The sensors are placed on a frame of fiberglass poles with rectangular or u-shaped cross section. This frame is approximately 175 cm by 100 cm in size, providing space for eight sensors at 25 cm cross-line distance. The size of the frame was adapted in width for transport in a closed, roadworthy trailer. Two additional gradiometer sensors could be mounted on extractable side-extensions on either side of the cart. Due to observed higher noise level of these two sensors, due to increased vibrations, it was decided to use a gradiometer array consisting of only eight fluxgate type sensors instead of ten, skipping one sensor on either side.

Figure 52: 10 Foerster FEREX CON650 gradiometer probes mounted on the cart. The wheels are independently suspended (© M.Kucera).

Foerster FEREX CON650 gradiometer probes were used as magnetometer sensors, measuring the vertical component of a 65 cm gradient of the earth's magnetic field with a sensitivity of 0.2 nT. In order to protect the sensors from the effects of the weather and to facilitate the cleaning of the system after fieldwork, the gradiometer probes are placed in sealed plastic tubes. In any case, the repeated monitoring of the physical measurement properties of the gradiometer probes is crucial for quality control and their maintenance. For the accurate global positioning of the measured data a Real-time Kinematic Global Navigation Satellite System (RTK-GNSS) rover (Javad Triumph or Sigma) is placed on the drawbar at 2 m distance from the sensors. As base for the RTK-GNSS system a second Javad Triumph receiver is used. The base was placed on official triangulated survey points maintained by the Austrian land survey office (Bundesamt für Eich- und Vermessungswesen).

Figure 53: GNSS receiver (rover) mounted in front of the Peli case, which holds the datalogger (© M.Kucera).

Next to the RTK-GNSS rover, an analogue-digital converter (10-channel EasternAtlas) is placed in a protecting casing (compare also Figure 53). All data is recorded on a ruggedized field computer (Panasonic Toughbook) mounted in front of the driver on the ATV. Initially, regular ruggedized laptop mounts have been used and fixed with two M8 screws onto the front rack of the ATV. After two years of operation these screws broke in case of one of the systems. This indicates the amount of force induced by vibrations during off-road operation, wearing and tearing the rigid connections. Now, the laptops are placed inside Peli cases padded with soft foam.

The specifically developed magnetic data acquisition and navigation software LoggerVis 2.0 developed by the LBI ArchPro (Sandici et al. 2013) combines the data strings of the GNSS unit and the magnetic data. It allows for the recording and storing of data and metadata (e.g. weather and ground conditions, operator names, etc.), the specification of the system used (e.g. cross-line distance of sensors resulting in the overall coverage width, sensor type and basic geometry of the cart) and the controlling of the on-screen real-time visualization of the system for navigation. Using the LoggerVis navigation screen the operator can navigate the system efficiently across the field and optimize the coverage. This feature is particularly useful on fields where the tracks of the cart and the ATV are not or hardly visible, such as harvested cornfields. For enhanced orientation and survey planning an aerial image can be displayed can be displayed in the background of the navigation screen, showing as well the already covered areas and possible gaps in the data acquisition.

Most important for the quality of the collected data is the feature of the LoggerVis data acquisition software to provide a quality control of the basic functionality and the physical characteristics of each fluxgate probe. Diagrams showing the actual noise level of each gradiometer can be visualized in order to detect malfunction, and a simple red/green color coding system alerts the operator if any sensor or the GNSS position data stream shows abnormalities or insufficient precision. Once all system checks have been performed and all metadata have been stored, the measurement can be started. The data is recorded along survey lines. Any recorded survey line can be of any length permitted by the data storage capacity of the system, for instance covering an entire field, without the need to be a straight line. During the measurement the quality of the positioning data is displayed. Usually, the recording of the data is stopped manually, when errors occur or when another sector of the survey area is to be measured. After interrupting the data acquisition of the current line, the operator can choose whether the collected data is good, should be kept, or can be deleted. If errors occur, standardized procedures help the operator to solve these problems in the field. Typical errors encountered include bad or no GNSS signal, and no data being recorded by one or more magnetometer sensors. In most cases, a faulty cable connection can be identified as cause of such faults, due to the constant vibration and mechanical strains on the survey system. The online data visualization provided by the LoggerVis software in form of a greyscale image is a very helpful tool for checking the basic data quality during data acquisition, and to ensure that all important features visible in the data have been mapped as completely as possible. In any case, the survey results should be checked carefully several times per day in order to ensure sufficient data quality and complete coverage. For this purpose a first simple data processing can be performed easily in the field using the default settings of the data processing software ApMag. This specialist magnetic data processing and imaging software has been developed for manually operated magnetometer systems by LBI ArchPro partner ZAMG, and extended through the ZAMG - LBI ArchPro cooperation to permit for the processing of large-scale high-resolution magnetic prospection data acquired with motorized survey systems. ApMag has almost constantly been adapted and optimized by its creator and developer Alois Hinterleitner through implementation of new filters to reduce the influence of the ATV on the probes, enhanced data positioning and direction depending filtering (Hinterleitner et al. 2013). It could be observed, that the influence of the motorized tow-vehicle on the data varies between different ATVs used, which is of importance when considering renting or acquiring new ATVs. Additionally, the characteristics of each sensor can and have been analyzed, in order to determine the individual noise levels and possibly problematic sensor behavior.

With this described magnetometer system setup it is possible to collect data at an approximate speed of 15 to 25 km/h, with a crossline sampling resolution of 25 cm, and a speed-dependent in-line sample spacing of 5 to 10 cm. Although the system is capable of collecting data even at higher rates, the mentioned speed limits should not be exceeded in order to warranty sufficient data quality and longevity of the entire system. Depending on the surface condition (roughness), size and shape of the survey areas/fields, which tend to be rather small and more complex in shape in the Kreuttal area, an average daily coverage of eight to ten hectares can be expected per system. The survey and fieldwork progress depends as well on the strategy employed to cover a specific field, and the skills and experience of the system operator. In order to cause minimum damage to the field and possible crops, the turning of the system should be carried out along the bordering field tracks. For best data quality the direction of measurements should be oriented in direction of ploughing, respectively harrowing. In 2013, already three of the described motorized multi-channel magnetometer systems operated simultaneously in the Kreuttal area.

Figure 54: Motorized magnetometers are operated at an average speed of 15 to 25 km/h (© M.Kucera).

In parallel to the survey with the fluxgate type magnetometer systems, a motorized Cesium magnetometer system was developed and tested in the Kreuttal case study area. The basic construction of the sensor cart stayed the same as with the fluxgate magnetometers. A total of eight optically pumped total-field Cesium magnetometers (Scintrex CS3) can be mounted on the sensor carrier. This cart was adapted to permit for different gradiometer arrangements, involving three height levels above the ground surface. The first level consists of five sensors, each mounted 44 cm apart at a minimum distance of 35 cm from the ground. The offset to the second level (comprising two sensors spaced horizontally 124 cm apart) and the third level (one centered sensor) could be arranged between 50 cm and 120 cm, respectively 200 cm above ground level. Currently, test are undertaken to improve the physical characteristics of the array in order to satisfy specific demands. Depending on the expected archaeological features with regard to size, depth and their physical properties, as well as the surrounding material, the gradiometer settings can be adapted.

The heavy electrical units and counters of the Cesium sensors are mounted on the tow-bar of the cart. Similar to the fluxgate type magnetometer system, four-channel analogue-to-digital converters connected in series are placed on the back rack of the ATV in a protective housing. In order to supply the necessary power, the generator of the ATV was modified to provide 24V output, and additional batteries were added. Providing a measurement resolution in the range of picoTesla, the Cesium magnetometer system is about 200 times more sensitive than the fluxgate gradiometers system.

Besides the large-scale magnetic prospection surveys, various small manually conducted prospection surveys were carried out in forested areas, applying both GPR and two different magnetic prospection carts equipped with three FEREX CON650 gradiometer probes and six Scintrex CS3 optically pumped total field Cesium magnetometers, respectively. The later Cesium magnetometer system had already been used ten years earlier for the prospection of other sites in the area (Neubauer 2001; Melichar and Neubauer 2010). The data positioning in case of the manually operated systems was realized in the traditional way using survey lines placed on the ground in regular grids. In a recent development, these carts have been modified to permit the integration of RTK-GNSS systems for automated data positioning.

Soil sampling and excavations

For an improved understanding of the detected magnetic anomalies, archaeological excavations and soil sampling surveys were conducted at the sites of Ochsenberg (an Early Bronze Age hillfort) and Hornsburg (a LBK settlement and two Kreisgrabenanlagen: Hornsburg 1 and Hornsburg 2). Soil samples were collected from 71 points at 10 m intervals on four transects trending north to south along the side of the hill west of the KGA Hornsburg 2. Sampling was conducted using a hand-operated Oakfield soil corer with a sampling tube of 24 cm length and 2 cm in diameter. The Oakfield soil corer eliminates the mixing of soil horizons and is thus useful for both stratigraphic characterization and the collection of samples for further analysis. Sediments were described in the field based on Munsell's soil color, soil texture, boundaries between layers, and inclusions. Soil samples were tested for available phosphate (Pav) using ring chromatography tests, or a spot test based on the method developed by (Gundlach 1961) and modified by (Eidt 1973) and (Bjelajac et al. 1996). This method has proven to be especially useful for the determination of the horizontal and vertical limits of sites, and for providing a general location of activities resulting in organic inputs

(Holliday and Gartner 2007; Salisbury 2016), and it integrates well with the surface collection and geophysical surveys (Salisbury et al. 2013). pH measurements were taken for 21 samples using an Oakton Acorn 6 pH meter and a 1:1 soil to water ratio.

At the site of KGA Hornsburg 1 an archaeological excavation was undertaken in 2013 and 2014, in collaboration with the Vienna Institute for Archaeological Sciences (VIAS) and the Institute of Prehistoric and Historical Archaeology of the University of Vienna. From the analysis of the geophysical prospection data a good state of preservation of the monument could be expected. It was decided to place the excavation trench on top of the western entrance gateway of the KGA, including both ends of all three circular ditches. Before the mechanical removal of the topsoil (plough layer and B-horizon), soil samples were taken.

The area was also mapped using a manually operated array of six Cesium magnetometers (Scintrex CS3) in a one to one gradiometer setup[43] before and after removal of the topsoil. The latter survey already revealed, together with the data of a magnetic susceptibility survey conducted with a Bartington MS3 kappameter, the archaeological evidence for structures inside the gate way. These structures turned out to be postholes, pits and remains of a smaller palisades, or possibly visual obstacles in the line of sight for anybody approaching the monument. Their presence indicates the good state of preservation of the monument. Additionally, the surfaces of the first deposits to be removed from the inner ditch were documented with magnetometry using the Magnetoscanner and magnetic susceptibility measurements (Kainz 2017).

Results

General aspects

Each archaeological investigation method allows only for specific propositions in relation to its general theoretical framework (according to the scientific discipline to which it belongs) and relative to the techniques applied and their inherent accuracy and precision (Kucera and Löcker 2007). Only well-defined investigation methods in the field of archaeological research can guarantee the reproducibility and comparability of the generated results. In order to limit bias in the data interpretation, each dataset gained through a specific method has first to be analyzed individually. While an entirely consistent treatment of the different datasets can never fully be expected, it should still be attempted by clearly distinguishing between the different methods during the first round of

[43] The so-called Magnetoscanner was designed by ArchaeoProspections® and modified by the LBI ArchPro. Its design should enable highly accurate magnetometer measurements by maintaining a constant distance of the probes to the ground, while moving them gently over the survey area to minimize measurement induced noise. While the Magnetoscanner is impractical for everyday large-scale geophysical archaeological prospection, it proved to be useful for the fixed framework conditions provided during the in extent limited excavation.

data processing and analysis. Once specific results are clearly established within the datasets obtained with different methods, these can be compared and merged for a closer integrative interpretation of the observed phenomena. Therefore, the main results obtained here with each methodological approach are listed according to the applied methodology.

Remote Sensing

Aerial photographs acquired over the last 70 years are the most important source for the thematic mapping of recent changes that occurred in the landscape of the Kreuttal case study. Although landscapes seem to be static when being travelled, aerial photographs can reveal a picture to the contrary. In the 1980s, most of the field systems dating back to medieval times were rearranged in order to facilitate industrial farming. Within a few years, old roads and hollow ways were relocated and the original ones disappeared. Thus, a first task in this study was to record the rather recently vanished features, including track ways and paths, field boundaries, and the course of power lines marked by their poles. This record of modern features is crucial for a correct interpretation of the datasets gathered for archaeological prospection; for example, a power line, which already has been removed but with the foundations of pillars still in place, is causing significant magnetic anomalies within the middle Neolithic settlement area of Hornsburg 2. While even more recent features may have already disappeared, evidence pointing to them could still be discernible in archaeological prospection data, permitting a temporal classified of the related features.

Comparison between archaeological interpretations based on aerial photographs dating back to the 1980s, and those of recent aerial photographs, suggests a decrease of observable archaeological entities due to continued or increasing erosion at exposed locations. This hypothesis has been supported by magnetic prospection, whereas the absence of some features within two different aerial photographs could have as well been argued with the variability of environmental and climatic properties. The observed disappearance of archaeological features motivated a general focus to be placed on the impact of accumulation and erosion processes on the available datasets. A general overview of the average erosion rates is provided by the Austrian ministry for agriculture, forestry environment and water management (BMLFUW). For a more detailed analysis, hDTMs based on IBM of aerial photographs from earlier flight missions were compared with recent DTMs gained from ALS. So far, the research focused on the description and analysis of the accuracy and comparability of the generated hDTMs, dependent on the provided photographic material and post-processing workflow (Sevara 2016). First results of the comparison of hDTMs and recent DTMs indicate significant changes of the local topography over the course of surprisingly short time frames. Without the knowledge of these recent topographical changes in the landscape, the collected prospection data might easily be misinterpreted. A more detailed study and discussion of this matter will be the subject of a separate paper (Sevara 2015).

The analysis of the available ALS data revealed various features and structures of archaeological interest, in particular in the forested areas. Whereas the site “Türkenschanze” has been known since the 19th century to have been a fortified hillfort covering some 85 hectares of area (Schad’n 1953), more detailed internal structures – such as terraces, pathways, field systems, and at least two construction phases of the bank – could be newly detected in the ALS data. The application of the analytical visualization techniques mentioned above, dramatically enhance the detectability for these faint features. In relation to heavy combats that occurred at the site of Ochsenberg during the final stages of World War II, traces of military activity in form of grenade launcher and tank emplacements, foxholes and bomb craters could be detected all over that area.

Field walking

The field walking surveys, carried out between 2012 and 2015, revealed artefacts dating from the Neolithic to modern times. The majority of artefacts collected could be dated to the late medieval period and modern times. At the presumed Middle Neolithic sites a typical variety of artefacts was documented, which can be connected to the settlement activities (painted pottery, a part of a stone axe, grinding plates and flints). Of special interest were areas that indicated a lower intensity of possible human activity according to the magnetic dataset. At nearly all of these areas, detailed raster and individual find location surveys suggest an archaeological relevance of the observed features. Currently, these results are elaborated in more detail as part of a doctoral thesis.

Geophysical prospection

From 2011 to 2015 six larger geophysical prospection fieldwork campaigns were carried out, each lasting for a minimum of two weeks, with one to three motorized magnetometers brought into operation. This magnetometry fieldwork resulted in a total coverage of 3.5 km^2 with areas mapped in the northern parts of the Kreuttal case study area, specifically around the village of Hornsburg and south of the village of Kreuzstetten (see also Figure 55). The collected magnetic prospection data revealed a multitude of archaeological features. Besides the known KGA monuments Hornsburg 1 and Hornsburg 2, various accumulations of anomalies observed in the data indicate settlement areas of the size of small villages and individual farm steads. Very prominent has been the discovery of several LBK houses and two presumably Iron Age settlements south of Kreuzstetten.

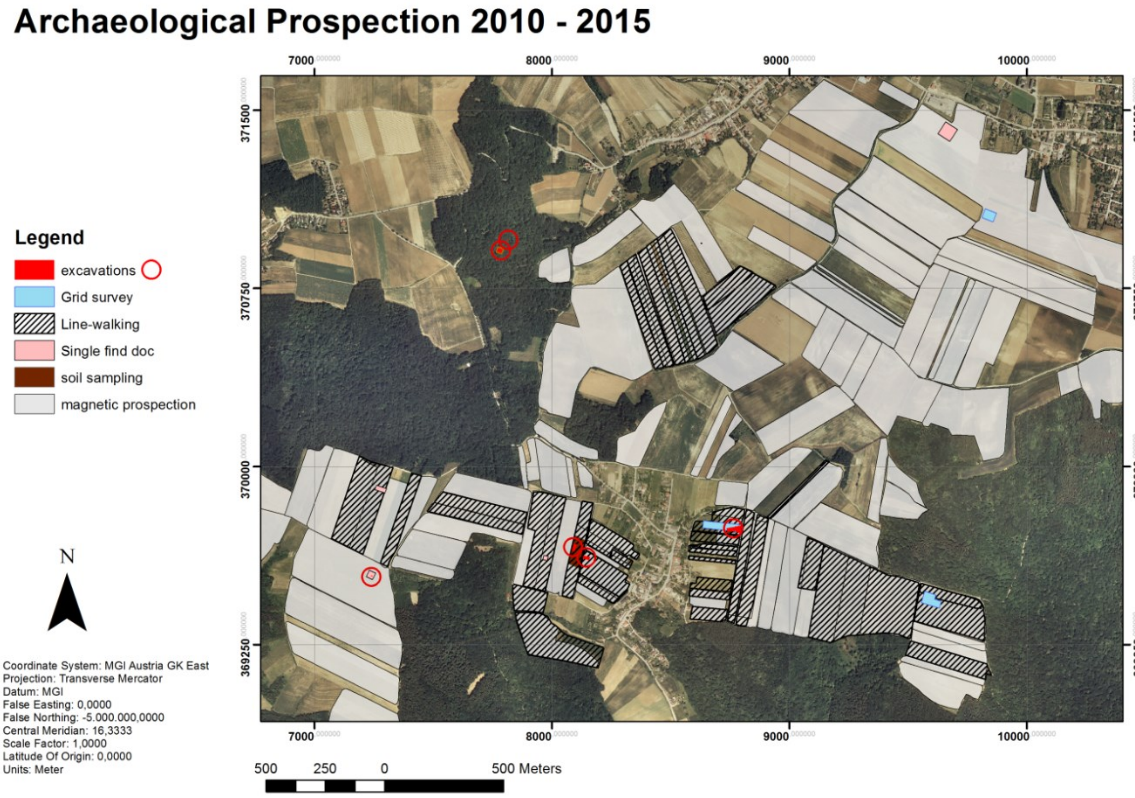

Figure 55: Total coverage of archaeological prospection in the Kreuttal area. Surveyed areas are indicated (© LBI ArchPro, M.Kucera).

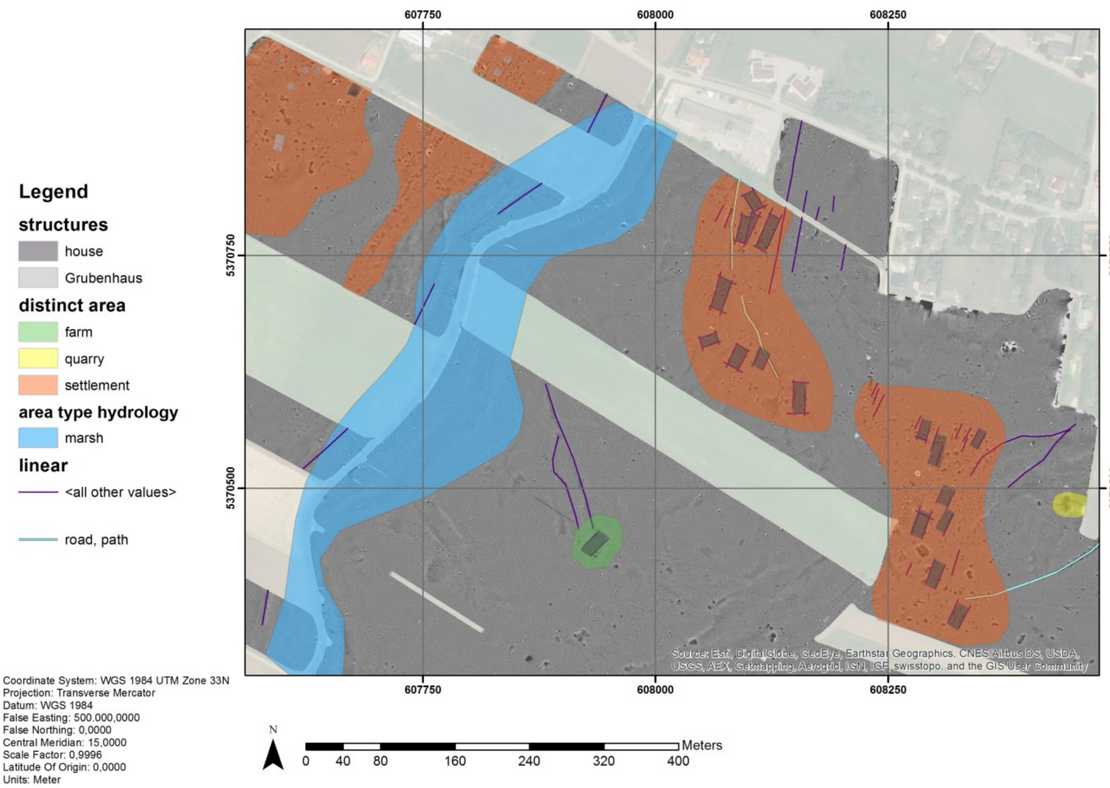

Figure 56: interpretative mapping of distinct areas south of Kreuzstetten indicating the location of a presumable LBK settlement (© LBI ArchPro, M.Kucera).

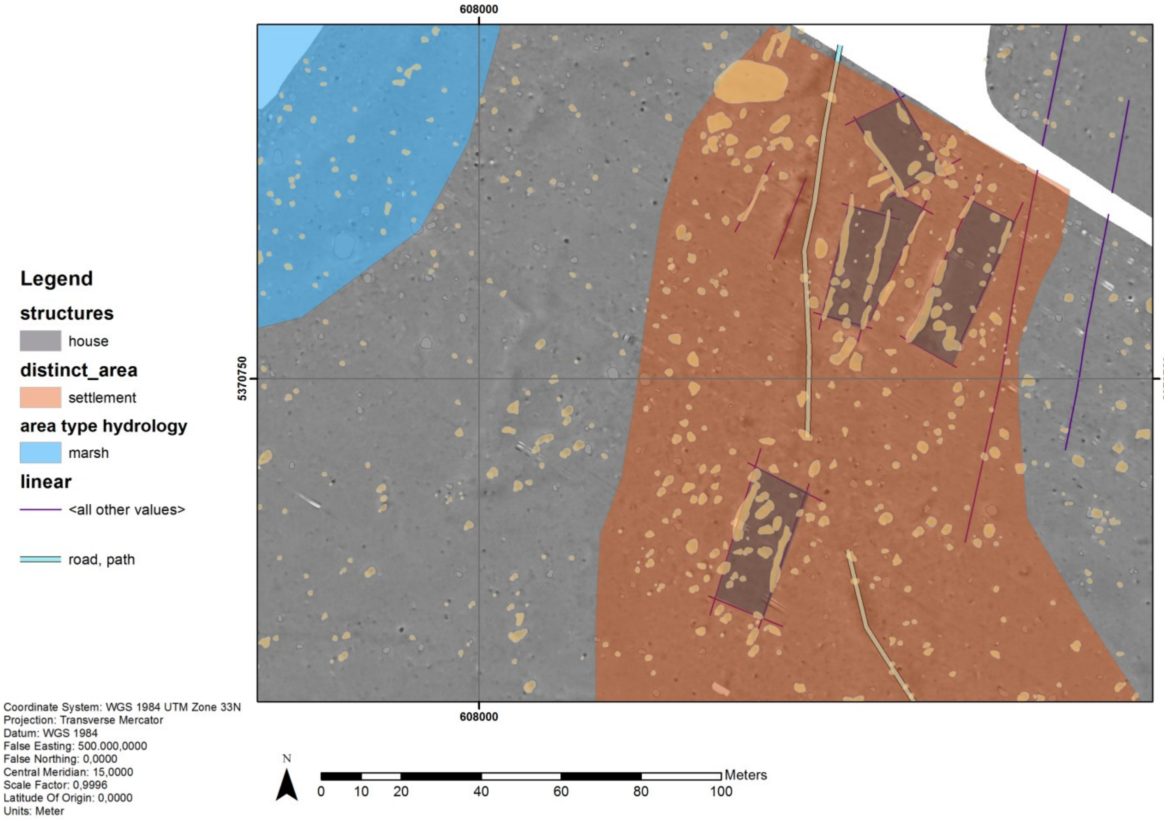

Figure 57: Detail of the LBK settlement with mapped magnetic anomalies (© LBI ArchPro, M.Kucera).

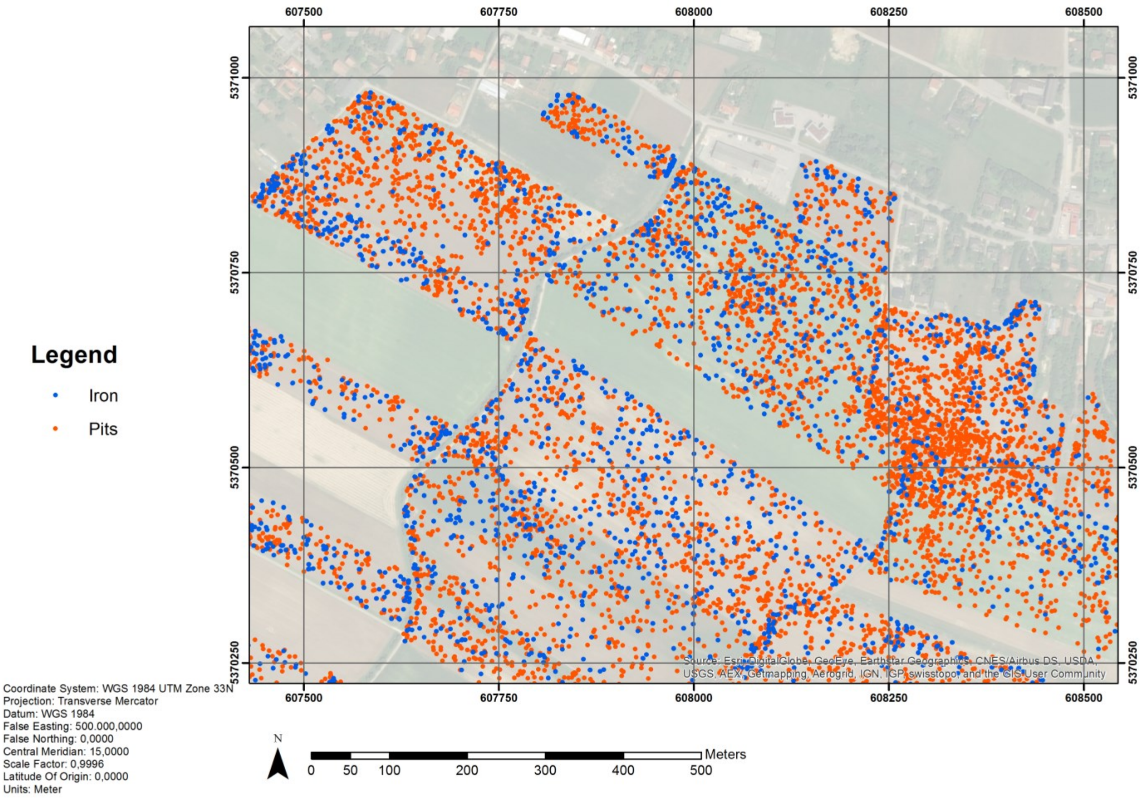

Figure 58: Distribution of magnetic anomalies caused by iron objects and archaeological features (pits). The location of iron often indicates old pathways (© LBI ArchPro, M.Kucera).

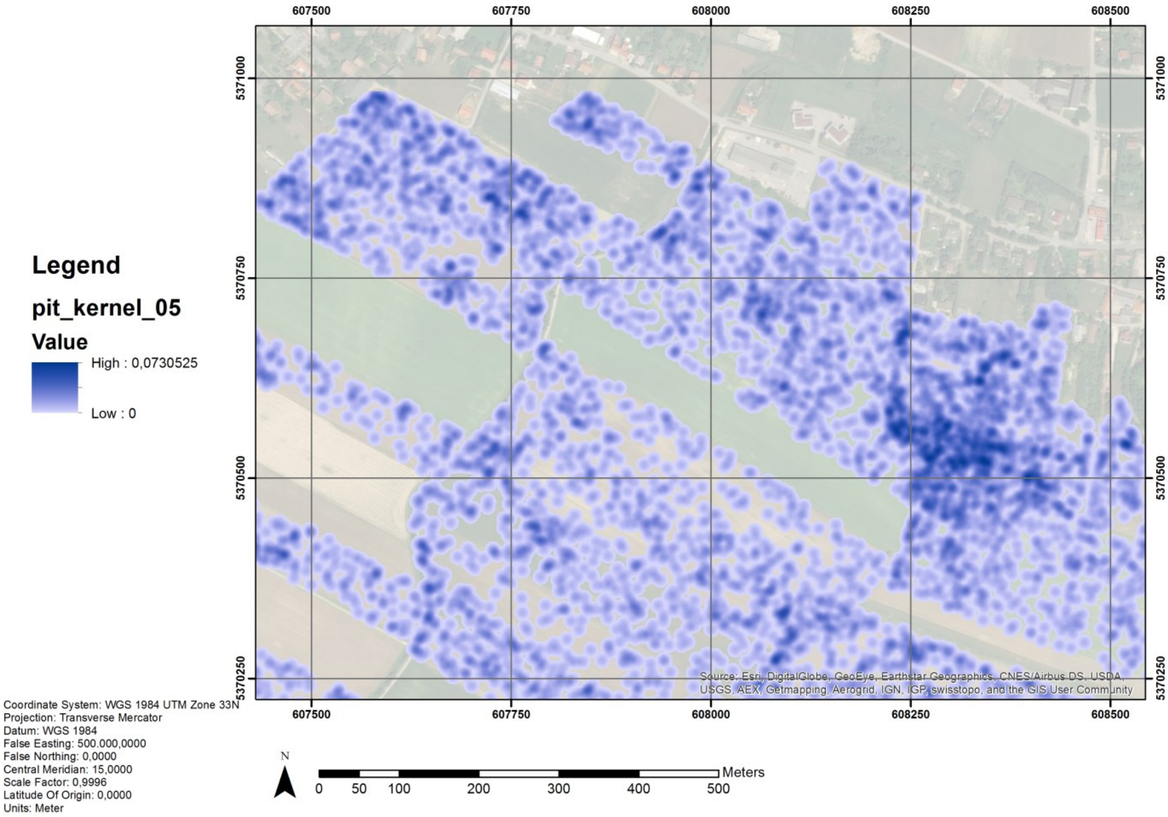

Figure 59: Point density calculated from the distribution of archaeological features (pits). Settlement areas and activity zones are clearly represented (© LBI ArchPro, M.Kucera).

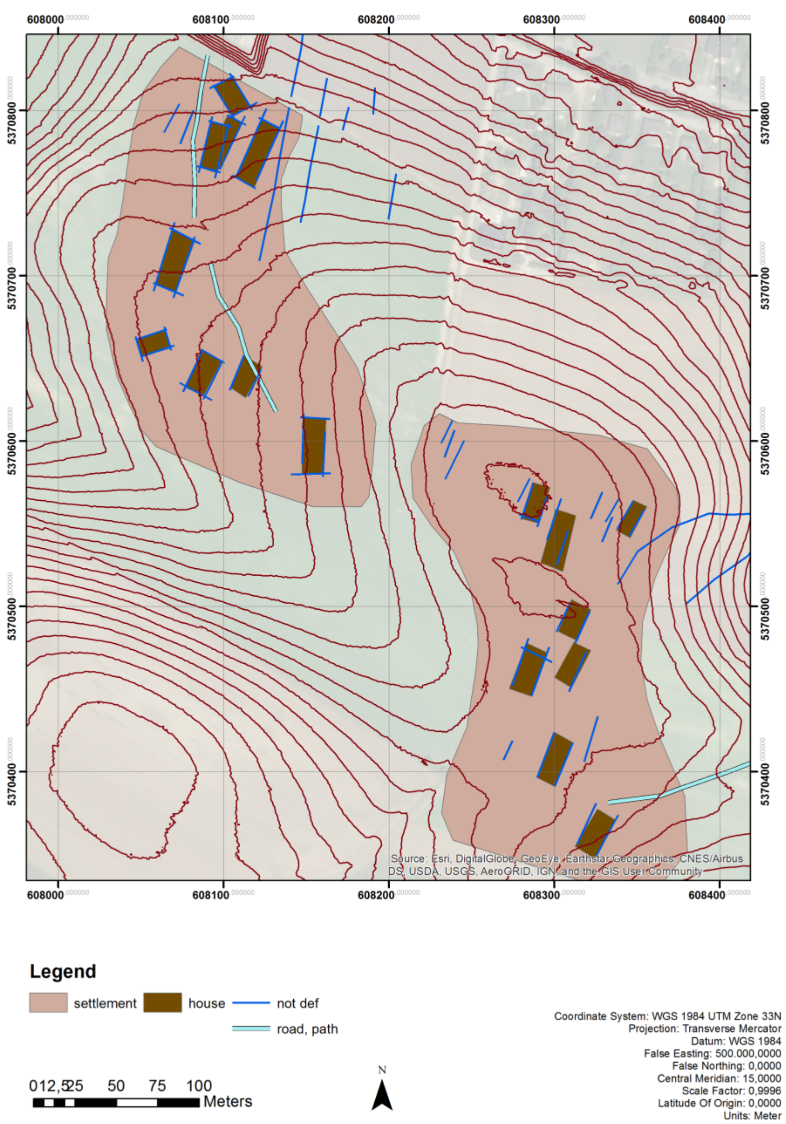

Figure 60: The location of the settlement respects the local topography (© LBI ArchPro, M.Kucera).

Although the density of observed archaeological features varies significantly across the entire study area, areas that are completely void of features of archaeological interest are rare. Even in areas where archaeological evidence is not to be expected, individual features and buried structures of presumably anthropogenic origin indicate past human activity. These features can only be interpreted through an integrated interpretation approach. Two of such structures should exemplarily be mentioned here: At a pass on top of the ridge to the west of Hornsburg, an arrangement consisting of four pits of the same size (2 m diameter) was detected in the magnetic prospection data. These pits were arranged in the shape of the letter T. A further, linear pit alignment was observed to the east of Hornsburg, stretching over a small plateau from southwest to northeast. These examples indicate the effectiveness of magnetic prospection data covering not only the expected settlement areas but providing information on archaeological remains contained in the entire landscape, including the perceived emptiness in-between known archaeological sites.

From a technical perspective, both logistics and operation of the motorized prospection systems could have been optimized. Investigations of observed measurement induced noise within the data resulted in a series of system and sensor tests, which led to a reduction of the number of probes mounted on the cart from ten to eight sensors. While during the initial surveys a considerable amount of time was spent every day on the testing and adaptation of the systems and their operation, with time the setup procedures became more and more effective. Fieldwork routines for system mobilization and operation were described in form of best practice guides, which proved to be valuable even for experienced personnel. Whereas expectations and predictions on daily coverage rates could hardly be met in the beginning, now daily production exceeds eight to ten hectares per system in the field. A standardized workflow including maintenance, transport, setup, operation and backup of the collected data was formulated and established.

The manually operated magnetic surveys carried out at Ochsenberg (Early Bronze Age multiple ring ditch and rampart enclosure) and Türkenschanze (presumably Iron Age fortified hillfort of approximately 85 hectares enclosed space) revealed settlement activities in the center of each respective site.

Soil sampling and excavation

The upper soil layer at Hornsburg 2 and the LBK settlement consisted of dark, yellowish-brown (10YR 4/4) clayey-silt with few or no inclusions, low organic content, and an average pH of 7.97±0.07 (n=20), representing a weakly alkaline soil. An abrupt boundary separated this modern plough zone from the underlying, light olive-brown (2.5Y 5/4) silty loess. Results of coring and sediment characterization at Hornsburg 2 and the settlement indicate that erosion has removed the original topsoil as well as an unknown quantity of the upper subsoil.

Despite the erosion, results of the available soil phosphate (Pav) analysis (Figure 61) indicate remnant patterns of anthropogenically enriched phosphate in the sampled parts of the site. Phosphorus and certain other chemical elements, as well as pH, magnetic susceptibility and organic content are elevated through human activities, such as slaughtering, cooking and other food preparation, fertilization, animal and human excrements, the use of fire, and waste disposal. Phosphorus, in the form of phosphates, is an element that remains fixed in the soil and is not easily removed through day-to-day processes of ploughing or natural chemical processes. Available, or labile, phosphates in soils are enriched primarily through the deposition of organic matter, especially bones, blood, and manure. Therefore, high levels of phosphorus strongly correlate with human activity (Parnell et al. 2002; Holliday and Gartner 2007). Elevated Pav values were interpreted as an indicator of patterned, intensive deposition of organic matter, most likely associated with human habitation and/or activities associated with the KGA. The obtained results correlate perfectly with the results of the excavation conducted in 2015. The excavation revealed archaeological features (pits, ovens, postholes), which were heavily affected by modern agriculture, and disturbed by a vineyard dating to modern times (presumably abandoned in the 19th century and therefore unknown to the locals). The recorded artefacts indicate a rich and exceptional variety of pottery, micro flints and even anthropomorphic figurines rarely found in a typical settlement setting from this period. A correlation with the nearby entrance of the KGA (excavated in 2009 and only 50 m distance away) could be assumed. In parallel, an excavation of a single feature (pit) detected by magnetic prospection proved the archaeological relevance of the observed anomaly. The pit could be interpreted as a cooking pit – based on the presence of fire exposed stones, having a usually size, the presence of charcoal, and the coloring of the surrounding soil –explaining the clear visibility of the corresponding anomaly in the magnetic prospection data.

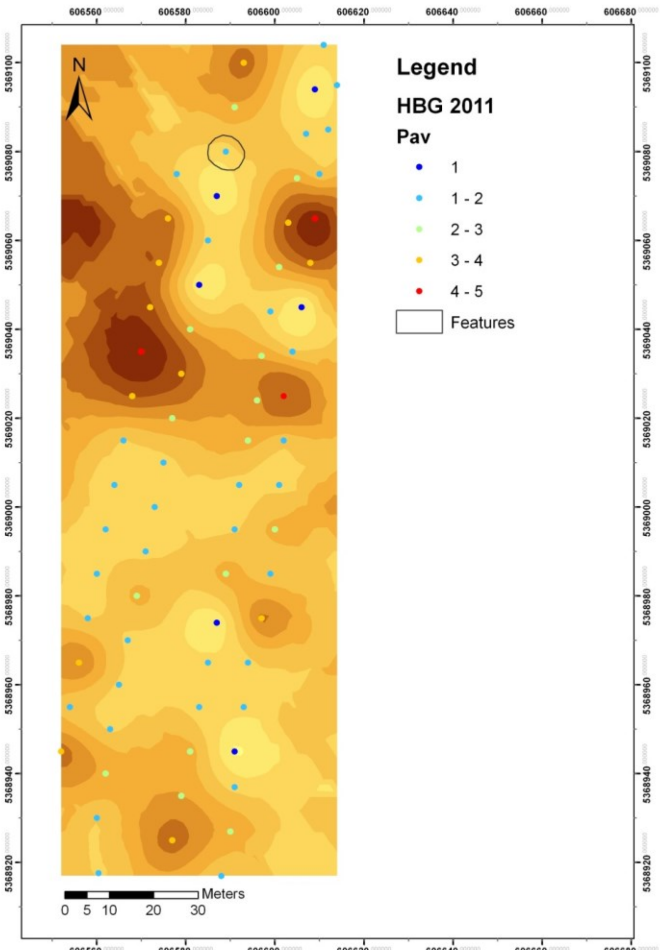

Figure 61: Distribution of Pav values based on soil phosphate analysis (© R. Salisbury).

Targeted excavations based on the archaeological prospections results were carried out at Ochsenberg in 2011 and 2012. Through these invasive investigations the monument could be dated to the Early Bronze Age. Several pits, which were already observed in the geophysical prospection data, were uncovered and demonstrated the potential of the applied methods in forested areas.

The excavations at the KGA Hornsburg 1 (2013-2014) proved the exceptionally well preserved state of this Middle Neolithic monument. Massive V-shaped ditches still preserved down to a depth of 4.5 m apparently had been carefully maintained through their existence. This observation is indicated by several documented ditch cleaning and maintenance phases. The temporal synchronization of the observed phases within every ditch is currently under investigation, based on the typology of the collected artefacts, radiocarbon dating, and the sequencing of the refill processes. For a detailed analysis of the material aspects of the refill processes various methods, including portable XRF, magnetic susceptibility measurements (Kainz 2017), geomorphological sampling and multispectral imaginary (RGB, IR, UV) combined with Image Based Modelling (IBM) have been applied. The latter image data have already been analyzed with respect to a possible semi-automated procedure for the classification of layers with different physical properties. This work, carried out within the framework of a diploma thesis, encourages further investigations regarding automated feature extraction based on multispectral imaginary (Schweighoffer 2015).

Discussion

So far, the overall Kreuttal dataset consists of magnetic survey data covering some 3.5 km^2, a complete coverage with aerial imagery from different acquisition years, a topographic model gained by ALS, imaging spectroscopy data, historical maps, field walking, soil sampling and excavation data, just to mention the most important components for the ongoing research. All of these data are available within a repository to be uploaded into the G-AIS. After carefully analyzing the results of every employed method, an integrated interpretation approach is crucial for gaining a closer understanding of the archaeological information content and context of these data. Within the physical and theoretical framework of the G-AIS, the reproducible comparison of different results and datasets is realized, and an integrated interpretation approach attempted. Spatial analysis tools provided by the Geographical Information System have to be combined with concepts for the investigation of temporal relations in the data and of the observed archaeological phenomena. Whereas in some datasets only a relative spatial superposition of archaeological features may be observable, other datasets may provide more precise knowledge on the stratigraphic relationships of these features. For example aerial imaginary can reveal that features are superimposed but not the respective sequence. GPR data allows volumetric analysis of the documented features and enables to derive a stratigraphic sequence for some of these features.

The spatial superposition of individual features or structures is often difficult to interpret, but it can be mostly addressed, when overviewing larger areas. Nevertheless, as soon as spatial superposition is detected or presumed within the dataset, no matter at which level, important archaeological information is provided and needs to be documented. Although a complete stratigraphic sequence of a given archaeological landscape could never be derived, at least some archaeological entities could be spatially ordered. For instance, the spatial superposition of pathways, earthworks and erosion channels at the site "Türkenschanze", as observed within the ALS data, was studied in detail during on-site visits. First interpretational arguments for the temporal development of this site are based on these observations. Again, the integrated analysis and interpretation approach is crucial for gaining new knowledge on spatial relations.

Whenever archaeological evidence is observable only in one dataset, this dataset has to be critically analyzed. By combining the datasets derived through magnetic prospection with topographical data and data gathered through field walking, the lack of archaeological evidence in one or two of these datasets can become understandable. At a settlement in the Kreuttal area, which could be dated through field walking to the Neolithic period, the distribution of artefacts seems to be relatively constant, whereas the magnetic data shows an absence of features in specific areas. By analyzing the topography gained through ALS, the absence of anomalies corresponds with zones of possibly higher soil accumulation rates. These rates could in a first attempt be estimated by the change of the pitch of the slope where the settlement is located. By interpreting the results of these three data sources (ALS, magnetic prospection and field walking) the contradiction of a constant distribution of artefacts correlated to human settlement activity, and the local absence of archaeological evidence in the magnetic data could be argued. Within a subsequent analysis, a DTM based on ALS data will be compared to an hDTM derived from aerial imagery dating to the 1980s. The comparison with low resolution data on recent average erosion rates already indicates significant changes that have occurred on the surface within the last decades (Sevara 2015).

When comparing recent aerial imagery with pictures from the early 1980s, massive landscape changes become apparent. In the 1980s, the legal structure and property borders of large regions in Lower Austria were restructured (during the so-called "Komassierung"), which led to the disappearance of old paths, track ways and field boundaries. These structures are still visible as soil and vegetation marks in some of the collected datasets. Where and when these features become observable in a specific dataset, depends on the type of the feature, the local soil and geological setting, and seasonal changes. An old track way may be visible within aerial photographs, while it may be invisible in the magnetic prospection data. It may only be visible in the magnetic prospection data when magnetically enriched material, such as rubble from a building, e.g. including pieces of bricks and roof tiles, was deposited along the way to compact the path. At another site, the underlying bedrock became visible within the magnetic data in form of meandering parallel anomalous bands. When compared against old aerial photographs, some of these bands (and only theses specific bands) are more likely to have been caused by old field borders that are still visible in the topographic data.

A large advantage of the archaeological prospection of entire archaeological landscapes is the possibility to explore the space between sites or zones of increased human activity and other features presenting archaeological evidence. An example is the recently detected pit alignment within the magnetic prospection data mentioned above. It is located on a small plateau heading southwest to northeast. The pits are approximately 2 m in diameter, and spaced at distances of multiples of 30 m. Although the appearance of this pit alignment is similar to the placement of poles of electric powerlines, no evidence for a recent intervention could be found within the other datasets. The alignment passes by a possible prehistoric settlement area, indicated by large arrangements of pits. The pit alignment ends up at the center of a very faint circular structure of about 80 m diameter. This structure is visible within the ALS data and requires further investigation in order to determine its origin and possibly function. During a field walking survey, no archaeological evidence has been found that could be linked to either the pit alignment or the settlement. By analyzing the topography, only minor erosion could be expected to have happened here, which may explain the absence of artefacts. In this case, only a targeted sampling survey or a targeted excavation could clarify the situation.

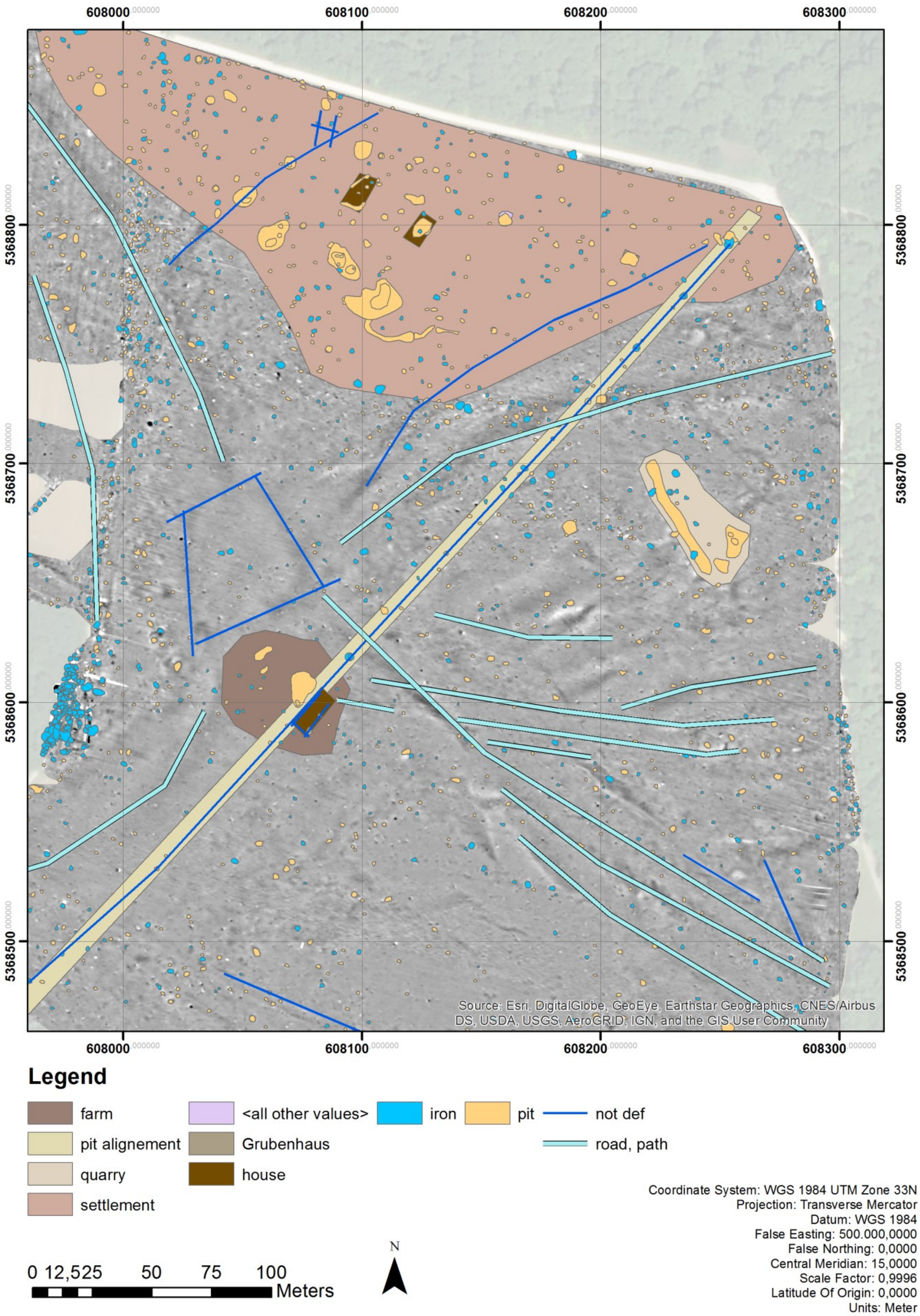

Figure 62: Interpretative mapping of magnetic anomalies on top of a digital terrain model (slope is visualized). A settlement area, a pit alignment and path systems were detected by magnetic prospection. (© LBI ArchPro, M. Kucera).

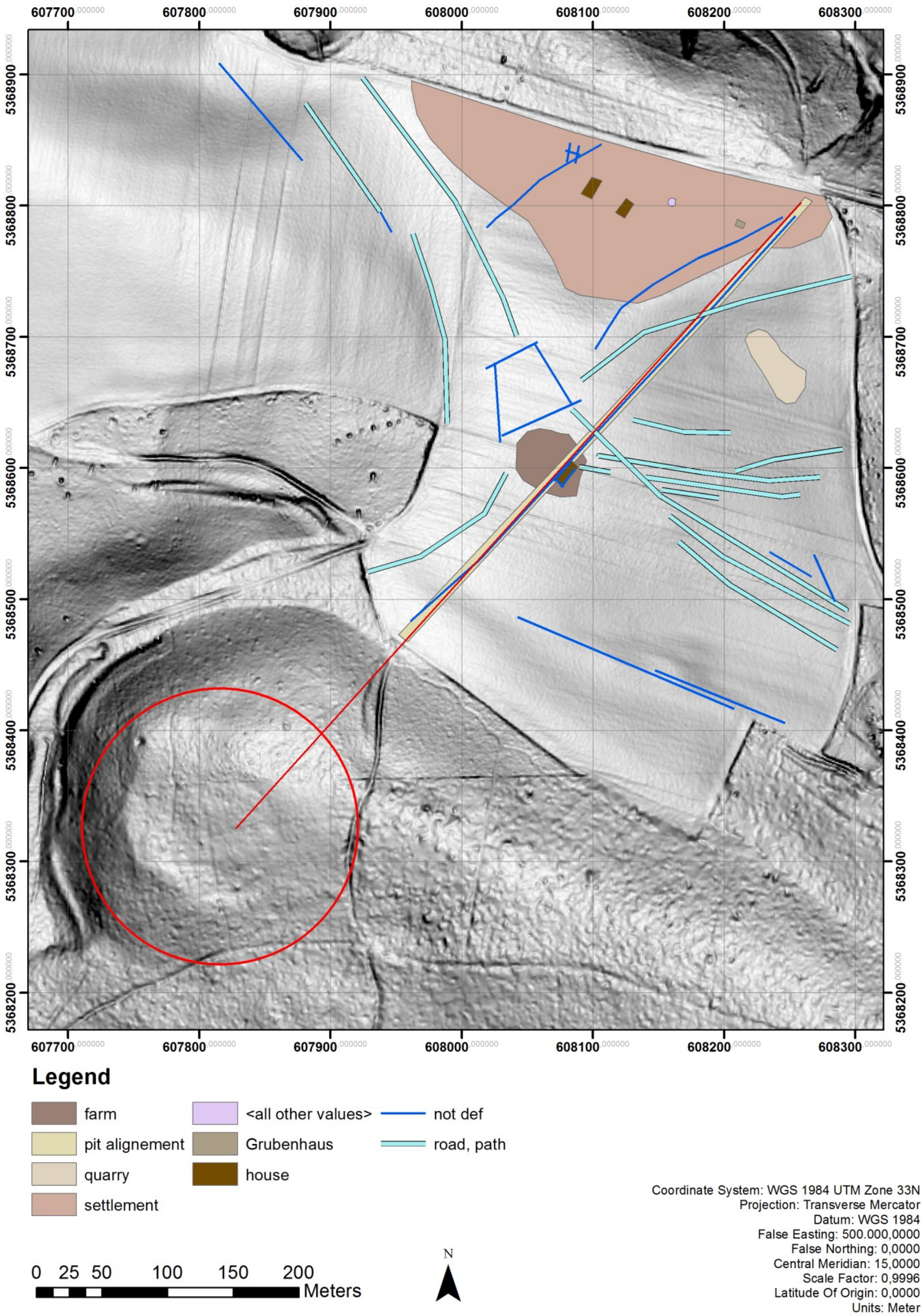

Figure 63: The pit alignment is oriented towards a circular structure (inside red circle) (© LBI ArchPro, M.Kucera).

Within a similar setting, a T-shaped arrangement of four pits of approximately two meters of diameter has been detected through magnetic prospection. Again, these pits are located on a plateau of a ridge on a faint topographic saddle. No corresponding evidence of human activity could be found within the other datasets, including field walking. A targeted excavation of one of the pits proved the presence of an accumulated soil cover, sealing the archaeological evidence. After removal of the topsoil, the pit only showed in the magnetic susceptibility data. It would have been missed entirely if only traditional excavation techniques had been applied.

Conclusions

In order to understand and interpret the spatio-temporal development of archaeological landscapes, a multi- methodological integrated approach is crucial. When archaeological information based on different datasets has to be analysed and interpreted, a GIS-based AIS proved to be the right tool to also secure the reproducibility of the drawn hypotheses. A standardized archaeological interpretation process, comprising data segmentation, data classification, and the analysis of spatial as well as temporal superpositions of interpreted entities, is crucial for the comparability and traceability of the generated interpretations. Each method or technique applied has to be well-defined in respect to its abilities, limitations, its accuracy, precision and validity to address or anseer a specific research question. One has to be aware that especially the outcome of archaeological investigations depends much on the posed research question itself, and the set of methods chosen to answer it. In this sense, a single methodological approach may be critical.

Only the expert combination of different, in their explanatory power biased methods, will allow for more specific conclusions to be drawn from the observed archaeological evidence, while interpretations based on a single methodological approach will not be as reliable. Furthermore, archaeological prospection on the scale of landscapes allows within a deductive process to focus on more detailed information, which in addition is gained by smaller scale surveys or invasive archaeological excavations. By displaying and understanding archaeological landscapes at a large scale, the context of the observed details can emerge and become comprehensible. Concerning the responsibility for the preservation of cultural heritage, invasive methods, such as archaeological excavations, can based on the prospection data be either planned as targeted keyhole interventions, addressing specific and well defined research questions, or possibly even be avoided altogether.

Although a traditional archaeological excavation appears to be comparably absolute in regard to displaying a physical reality, it only reveals what we try to find depending on our experience, prior knowledge and methods used. The absence of evidence in one or more datasets does not prove its non-existence or existence. In contrary, negative evidence allows for the critical discussion of the applied methods in this specific context, in order to find an explanation for the lack of evidence, since "the lack of evidence is not evidence of lack" (Huber 2016), a fact well understood in exploration geophysics.

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Discussion

Principles of multidisciplinary interpretation

Every archaeological site is unique. This statement can be seen as a basic principle valid for all archaeological disciplines and research questions. But it is not just the geographical location and the local environment that is specific: it is also the material component of found artifacts and ecofacts. As archaeological evidence is generated by human beings it is highly dependent on the respective human society under investigation. Furthermore every interpretation of the origin and functionality of material remains is based on a recent and very subjective perception of the world. The main aim of every scientific research is to achieve maximum objectivity regarding the description of observed phenomena. But similar to quantum mechanics, where the collapse of the probability wave is caused by its observation, the interpretation of archaeological evidence is strictly related to the person observing and investigating this evidence. In this respect an archaeological excavation can be seen as an experiment or observation, which determines discrete stratigraphic units (Löcker and Kucera 2009)[44]. The results of an excavation and therefore the derived stratigraphy of a site, is clearly dependent on the skills and experience of the excavator.

This also seems to be true for the interpretation of archaeological evidence through archaeological prospection and is related to the anthropogenic nature of the observed phenomena. Human life is generally influenced by physical reality and human reality (Pietschmann 1990; Wallner 1996). Whereas physical reality must be expected not to have changed, human reality, i.e. the subjective perception and experience of the world, is specific for every human society, probably for every human being. That is the basic challenge of every archaeological research: the material evidence, which has to be interpreted, is based on physical and human reality. Archaeologists want to investigate this past human reality by analyzing the (physical) environmental parameters in order to derive knowledge of past human societies. Personal experiences and expert knowledge are very important for the generation of archaeological interpretations, but also seem to lead to a limitation on interpretations, which are comparable to known phenomena. In this respect the ambivalence of the person, who created archaeological evidence and the person, who analyses it, can be derived (Kucera 2004). Both are controlled by physical reality and their subjective human reality.

In declaring, that the aim of archaeology is to investigate the spatio-temporal development of human societies based on physical and human reality, the multidisciplinary character of archaeology becomes evident. Natural sciences are needed, whenever the physical reality must be analyzed and

[44] This experiment is not reproducible, if the aim is to investigate archaeological theories. It is only reproducible in respect of generally testing the laws of stratification.

described. Based on the material evidence of past human societies and the analysis of ecofacts the physical environment can be investigated. In this respect it must be stated, that natural sciences are always dealing with the question of "how". In contrast, natural sciences are not capable of answering the question as to "why" a phenomenon is observable, as this question represents the sphere of human reality and has no relevance for natural sciences. This part can be examined in applying the scientific methodology of the humanities. Whenever a phenomenon, which is anthropogenic, is observed, all aspects and research topics of humanities have to be taken in account[45].

Consequently, archaeology cannot achieve common valid results and interpretations without a multidisciplinary approach, as archaeology is already multidisciplinary. The challenging question seems to be, what the basic principles could be and how a multidisciplinary approach in archaeology can be theoretically realized.

Since the 20th century interdisciplinary or multidisciplinary research related to archaeology has enormously extended the scientific archaeological toolbox. Nowadays a portfolio of various techniques and methodologies derived from nearly all disciplines exists. These investigate archaeological and related phenomena in great detail. The application of these methods has seen increasing use during the last 40 years (Butzer 2009), which has lead to the introduction of "new" disciplines, such as geoarchaeology, archaeobottany, dendrochronology and archaeological prospection techniques. Most of these disciplines were primarily developed for other studies, but found practical and promising application within archaeological research.

Every applied method is capable of describing and analyzing a specific detail of a phenomenon. Some of these methods and their respective results have been exemplarily described within this thesis. The choice of the set of methods is determining possible results in advance and must be argued carefully. It significantly influences the focus of research and biases further investigations. To stress a metaphor, the scientific target is placed in this way[46]. The results of every method must be interpreted regarding their principle validity described by the respective theoretical background of every discipline. Therefore this methodological background as well as its limitations regarding the answering of respective research questions must be well-defined.

From these statements several basic principles for a multidisciplinary approach can be derived. Every applied method must be well-defined regarding its theoretical background. Without a clear

[45] The location of a settlement might be explained by a specific topography and principal presence of resources, but it is also highly related to the subjective preferences of a human society. It is also part of archaeological research to specify the amount of influence of physical and human reality to best describe observed phenomena.
[46] Compare also the discussion of the pXRF results (pp.92).

definition, any results gained would be arbitrary and in contrast to the basic principle of the theory of science regarding the reproducibility of results. The theoretical and practical framework of every method must be stated including reliability within a given context and validity range of respective results. Without this a comparison of results gained even by the same method applied on different archaeological contexts could hardly be achieved. For this purpose a fundamental knowledge of the applied method and the context on which it is applied is crucial. This implicates the formulation of a clear preceding research question. As most applied methods have been developed within other disciplines and demand a profound knowledge of the respective techniques and fundamental theoretical and practical modalities, the formulation of a specific research question must be based on a scientific dialogue of respective experts. This is a crucial and challenging moment in archaeological sciences, where a wide spectrum of discrete knowledge is demanded. Ideally this should result in an interdisciplinary dialogue and the collaboration of scientific disciplines and experts. Within this process it is still very important to separate the single disciplines and be sure of their principle abilities to answer respective research questions.

Once the set of methods to be applied is chosen for a well-defined research question, data acquisition can be started according to the methodological principles and demands of every single method. Based on a clearly defined methodological separation, the later reproducible integrated interpretation of multidisciplinary datasets is enabled.

Multidisciplinary interpretation routines

A basic demand for the successful integrated interpretation of multidisciplinary archaeological datasets is to optimize the correlation and interaction of available information. As all archaeological data has a spatial reference GIS-based data management and analysis provides the necessary platform to organize and compare the results of different datasets. Usually GIS is capable of displaying 3D data, thus must be adapted to solve 4D relations including the temporal component. For the comparison of different acraheological artefacts and ecofacts regarding their archaeological and physical properties additional databases have been created. The main aim of these databases is to guarantee the controlled detection of analogies (also regarding typology, provenience and material component) within the archaeological finds and findings (Stadler and Kutschera 2005).

Besides the necessity for spatio-temporal analysis in archaeology, the implementation of a temporal component within GIS was also recently applied for supporting the logistical problems of companies, monitoring of flooding events (Kurte and Durbha 2016) and other topics not related to archaeology.

For the spatio-temporal recording and analysis of archaeological data a clearly specified GIS-based archaeological information system (G-AIS) proved to be useful (compare also (Carver 2005).

The suggested G-AIS solution includes several tools for stratigraphically sequencing the data (HMC+), for managing (i.e. creating optimized geodatabases) and interpreting the data (ArchaeoAnalyst). For the 3D display of the data the ESRI platform ArcScene can be used. For more complex geometries additional 3D viewers can support the visualization of the data together with different data sources (Arch4DInspector). The G-AIS defines the practical framework for every integrated data interpretation. Of course the system is also capable of dealing with a single dataset using all spatial analysis, visualization and filtering tools provided by GIS.

In order to guarantee reproducible results derived from integrated data interpretation, standardized routines and workflows are in demand. This includes data acquisition, processing and visualization. Again the uniqueness of archaeological phenomena plays a crucial role for the specification of standardized routines. A successful GPR survey is dependent on various parameters including applied systems (frequencies and antenna types), the geological and pedological setting, humidity, permittivity (to a small amount also conductivity and permeability) of the soil and the topography. In general even two surveys carried out at the same place can provide different results, if the environmental setting has changed. For this purpose a monitoring and recording of the different parameters is necessary.

When including additional information derived from material analysis, it must also be mentioned, that most results are hardly quantifiable. Although basic processes (e.g. smelting, forging, surface treatment) composition of the material (alloys, ceramics) and provenience can be investigated, most materials have also been transformed through usage and deposition (e.g. transformed by corrosion). Results seem to be qualitative but can be relative compared to similar datasets, if the analyzed material can be expected to have been exposed to comparable treatment and processes.

In this respect it is very important to record not only single objects or sites but also provide the data of the phenomena they are compared to. Analogies are the basis of every archaeological research and need to be carefully documented.

Regarding data acquisition, two issues must be obeyed: how and why the data was collected. First as much as much additional information possible about the survey must be recorded. This includes the setup of the applied systems and the survey strategy but also environmental parameters. For later GPR data interpretation, documented weather conditions (e.g. rain) and terrain (rough, smooth) are an important information for refelcting the quality of the data. Secondly it must be argued as to why a specific experimental setup was chosen including the predefined research question. This can be stated in correlation to previous experiences. These data can be referred to as the metadata of a survey and are crucial for the methodological analysis for the further optimization of applied techniques and for the investigation of interfering parameters. In this respect the uniqueness of the archaeological material also has the potential to observe unexpected dependencies of different phenomena in a multidisciplinary approach.

Once the data is collected it must be processed according to well-defined procedures. Every processing step can lead to the annihilation of raw data or the creation of artifacts. Especially when filtering the data to minimize noise in geophysical prospection this must be taken in account. A strict documentation of the applied processing steps and filters is necessary in order not to lose information or generate artifacts.

Before all multidisciplinary data can be interpreted within an integrative approach, every single dataset must be analyzed regarding the specific demands of the theoretical and practical background of the respective method. Whereas basic archaeological knowledge is helpful, the main objectives are the skills and profession of the respective scientist. If geophysical data must be interpreted regarding its geophysical background, this must be done by an expert on the specific research topic. Only on this basis can a reliable basic dataset be created, which represents first of all the geophysical evidence of presumed archaeological features. Without geophysically biased mapping of the data, it must be emphasized that results will be arbitrary. Geophysical prospection has often been criticized for not revealing archaeological evidence, as it was later found by an excavation and vice versa. When archaeological evidence is missed by a geophysical survey or in general by archaeological prospection several reasons can be found. In most cases it is the poor or missing physical contrast of the archaeological feature and the surrounding soil. Unfortunately the reason might also be bad decisions regarding the applied method and experimental setup or just simply the wrong moment. Again, if metadata has been collected, it can be used to analyze the reason for the absence of the feature within the archaeological prospection dataset. It might also be useful to compare and analyze soil samples collected during the excavation or even to accompany the excavation by a geophysical survey. For this purpose susceptibility measurements are the most common methods applied. If a feature is detected by geophysical prospection, i.e. the material contrast of a feature depending on the used sensor is documented, this feature exists. If it is not revealed by an excavation, it might not have been archaeologically relevant or the material contrast was not visible for the sensors used at the excavation. These sensors are normally the basic human senses. (compare also (Löcker et al. 2015).

As soon as the data is segmented and classified according to their physical properties an expert-biased archaeological interpretation can be started for every method. This is one of the scientifically most challenging steps, as expert knowledge in archaeology (especially regarding typological analogies) and also elaborated skills within geophysical context is needed. This also illustrates the fact, that geophysical data provided without proper interpretative mapping of the observed features is highly critical. Archaeological results derived from such data are rarely reproducible and hardly reliable (compare also Neubauer 2001).

After this primary method separated interpretation process, the results can be integratively interpreted again. Although it seems that data could be combined earlier, in this case the results lose their traceability. For example, a volume defined by GPR data and representing buried debris along a house structure is characterized by a strong thermo-remnant anomaly in magnetic data. It could be easily interpreted as debris consisting of bricks or tiles, but without separate interpretation important information is lost for later analysis.

If the archaeological interpretation of a single method is a difficult task, then the integrated interpretation of multiple datasets is even more challenging. A basis for a successful and accurate interpretation is at least a multidisciplinary approach, where different experts provide information and collaborate. To provide a general basis for integrated interpretation and in order to guarantee reproducibility and comparability of all results, a well-defined acquisition, processing and single method interpretation workflow can be applied. All data and metadata representing these different work steps are managed, analyzed and visualized by G-AIS.

Benefits of multidisciplinary data interpretation

All archaeological research deals with open systems as its main topic of research. Archaeology in particular is confronted with a double open system as it interacts with a social and a physical environment. This results in a situation where all parameters influencing and initializing specific archaeological evidence can very rarely be determined or observed. All knowledge about archaeological evidence derived from observations is therefore limited to the applied methods and observed parameters. This knowledge is represented by results based on routines regarding data acquisition, processing and interpretation. Due to this, these results are traceable and reproducible. Like all scientific results they are of hypothetical character.

It is a major issue of archaeological research to completely describe and explain archaeological evidence and its relation to other observed phenomena. Usually only known things are found. This general statement is also valid for excavations and the interpretation of archaeological data (respectively all data). Based on this, it seems impossible to derive a complete picture or interpretation of archaeological evidence. If multiple methods are applied, specific archaeological theories and hypothesis can be supported and elaborated.

Results and therefore theories and hypotheses can be never verified but according to Popper only falsified if a contradiction appears (Popper 1994; Schülein and Reitze 2002). Corresponding to the axioms of Aristotelian logic (Pietschmann 1996), only one of these results can be correct. If these results are based on a single method, all work steps must be controlled in order to find errors or evidence of bad data. In applying only approved methods this will be most likely the case. Otherwise the method and it specific application on the given archaeological context must be critically analyzed and studied again. It might be that the method is not suited for the respective research problem or not well enough elaborated.

Of greater importance are the revealed contradictions of hypotheses derived from different methodological background and techniques, as they reflect the capabilities of integrated interpretation of multiple datasets. First all single results must be controlled regarding their reliability, which again is only possible if all metadata is available. If even the results of two or even more methods are in contradiction, one or more hypotheses must not necessarily be automatically abandoned. This fact could also signal the appearance of a new parameter which has thus far escaped detection. Without a discrete archiving of metadata, the reliable exposure of thus far unknown phenomena and relations is impossible or only made by chance. Integrated interpretation based on previously well-defined routines enables the traceability of observed conflictive phenomena. Whereas a single method based approach can only reveal contradictions, integrated analysis provides the possibility of extending knowledge of interfering parameters.

A very positive example where the contradiction of two results gained by humanities and natural sciences caused a major impact on the methodological development of involved disciplines is the dating of the volcanic eruption of ancient Thera (Santorini/ Greece). Based on the need for a temporal synchronization of civilizations in the Eastern Mediterranean (second Millennium B.C.) an interdisciplinary project (SCIEM 2000) was launched (Bietak and Czerny 2003). A basic idea was to use the analysis of tephra, which can be found in various stratigraphic layers throughout the Mediterranean, as a temporal tracer. As the provenience of the tephra can be related to eruptions of specific volcanoes, they can basically serve as a time stamp (Peltz and Bichler 2001). The relative dating and synchronization of archaeological phases and layers of different archaeological sites became possible also by material analysis.

Originally the Minoan eruption of the volcano of Santorini was dated to the time interval 1450 to 1650 BC (Peltz and Bichler 2001), which also fitted absolute egyptological timelines, mainly based on the excavation at Tel el Daba (Höflmayer et al. 2016; Bietak 2012). Several organic material, which can be related to the Minoan eruption of Santorini, were used to date the eruption to late 17th century BC (1627-1600 BC, (Friedrich et al. 2006). This date caused a discrepancy between the absolute time line corresponding to the temporal analysis of the stratification revealed at Tel el Daba and the radiocarbon dating results by approx. 80 years (Höflmayer et al. 2016). Radiocarbon dating of organic material collected at Tel el Daba itself, also revealed this discrepancy (Kutschera et al. 2012). Since the first contradictory results were published, all participating disciplines examined sources for possible misinterpretation or incorrect results. One explanation regards the elevated presence of fossil carbon, which might influence the vegetation and therefore dateable material on the island of Santorini. This elevation of fossil carbon within the samples might be due to volcanic activity and the related emission of volcanic carbon dioxide (Bruns et al. 1980). Investigations showed, that known volcanic vents on Santorini are far away from the locations, where datable material was found (Kutschera et al. 2012). Additionally, material that can be correlated with the Minoan eruption, indicates the same time interval suggested by samples from Santorini (Manning et al. 2006). Recently deposits from the costal site of Palaikastro/ Crete revealed tephra and volcanic ash, which could be identified as originating from Santorini. These deposits suggest a tsunami caused by a volcanic eruption. Radiocarbon dating of organic material found in the same deposits, related the observed event to the Minoan eruption (Bruins et al. 2008). All these detailed results were motivated by an initial contradiction based on interdisciplinary research.

For a single, method precision and accuracy are the most important parameters to characterize the reliability and also validity of an experimental setup. This approach is crucial to guarantee the comparability and reproducibility of lab-based results. Every experiment in natural sciences must be reproducible, quantifiable and analyzable according to the given precision and observed accuracy (Pietschmann 1996). All interfering parameters must be suppressed. Results must be reproducible within a respective error range with the same experimental setup and conditions. Archaeological research is most often not lab-based. Collected data are dependent on various and changing parameters, which are hardly observable and controllable all the time. The demand for the reproducibility of a specific dataset regards the same experimental setup, the same spatial environment and setting, i.e. instrumentation must be placed at exactly the same geographic location, with the same orientation under the same environmental parameters. This is nearly impossible. The integrated interpretation of different methods of archaeometry has proven that the basic source of relevant information is not the single object, but the comparison of different ones. The search for patterns and analogies is also a basic principle of archaeological methodology.

For the interpretation of physical or chemical data it could be argued, that the respective accuracy and precision of an applied method is not as crucial as in the natural sciences. Nevertheless it is still very important for metadata to be stored as the basis for later comparison. For comparing different results it is more convenient to define a specific threshold. This threshold is also based on the principle accuracy and precision, but often more related to the examined material and the detection limit of a specific parameter (element). As illustrated by the on-site application of p-XRF, it is of greater relevance to detect tendencies and describe results in a comparative and qualitative way. This is also reflected through the rising amount of in-situ measurements at archaeological sites and excavations (Frahm et al. 2014; Hausmann et al. 2017; Dalan et al. 2017).

As all observed phenomena represent the relative contrast of one or more archaeologically relevant (anthropogenic) parameters to the physical or chemical background, respective results are mostly relative as well. If these results, also derived from different methods, are relative, only an expert-based multidisciplinary approach is capable of comparing them. In this case not only archaeological research benefits from this approach. Every single discipline is challenged by varying settings to critically analyze the respective applied techniques within the empirical and theoretical context of each discipline. It often also implicates the application of a technique within a completely different environment, for which it had not been primary designed.

In the research field of constructive realism (CR) in the theory of science, this would be a perfect example for strangification. According to the ideas of constructivism, science constructs reality based on made observations (Schülein and Reitze 2002). This construct always only represents the aspects within the applied methodological context and is therefore limited. CR postulates that knowledge and therefore constructive interpretation can increase, when a known phenomenon is set into another context and interpreted from this perspective (Wallner 1996). This illustrates the relevance of the archaeological disciplines for all scientific disciplines. Multidisciplinary collaborations are capable of considering scientific interpretations from different perspectives. These perspectives are also subjectively influenced by the basic theoretical framework of the humanities and natural sciences.

Finally only the integrated interpretation of multiple datasets enables the spatio-temporal analysis of archaeological evidence. It must be integrated, because state-of-the-art archaeological research is based on a multidisciplinary approach and depends on the collaboration of various disciplines. For this purpose expert knowledge of every applied method is crucial and a multidisciplinary academic dialogue must be emphasized. All collaborating disciplines can benefit from this dialogue. The development towards 4D recording and its respective analysis tools introduces new techniques and methods not only for archaeological purposes. In addition to these practical issues, formal theoretical frameworks regarding the interval based temporal interpretation of processes and their spatial relation can be introduced and argued.

Limits and pitfalls of multidisciplinary data interpretation

When stating that (1) applied methods determine respective results, (2) archaeological material can be characterized by its uniqueness and (3) nearly always, but not all, interfering parameters are known, archaeological research might risk becoming arbitrary. As highlighted, only strict routines and standards can guarantee the reproducibility and comparability of data. Keeping in mind the big amount of data and the huge variety of applied methods, this is a challenging task.

When archaeological data is recorded, it must be constantly determined, which kind of further analysis could possibly be useful. This is very important, whenever destructive methods, such as an excavation are applied. Every further analysis demands specific sampling and data acquisition routines, which often interfere with other techniques. In general, samples for chemical, physical or biological analysis (e.g. Radiocarbon samples, samples for ancient DNA or morphological analysis of bone) must be treated according to well-defined standards to avoid contamination. The sampling according to these standardized routines sometimes impedes the archaeological documentation process. In this case it has to be decided on site, which standard must be respected. It is crucial to indicate and argue this decision, as it is important for the further interpretation and weighting of the results.

Much fundamental research has been done toward guaranteeing standardized and scientifically approved workflows for data collection (including excavation rules, sampling strategies, sample treatment, etc.) (Gowlett 1987; Asscher and Goren 2016; Frahm et al. 2014). Unfortunately they cannot be obeyed all the time. The reasons are the potential for the aforementioned conflicts between the specific demands of two or more methods and again the uniqueness of every archaeological site or phenomenon. The latter indicates uncertainty concerning the type and structure of archaeological evidence, which is especially revealed during invasive sampling surveys or excavations. Very often it is only during the excavation campaign itself, that the necessity for specific sampling, prospection and analysis strategies is recognized. As the composition of the additionally applied methods of archaeological sciences depends on the specific archaeological context or phenomenon, it is rarely foreseeable for the most part. This must be taken in account, when the quality of samples provided must be argued. Both, the reason for the status of the quality and the quality itself have to be described and documented.

In interpreting multidisciplinary datasets within an integrated approach, a close collaboration of various disciplines is crucial. Additionally it is very hard to determine, whether a statement or observation reflects trivial results. In the case that another discipline must be included, this means that certain aspects of observed phenomena are no longer trivial. A solution for this is consequent communication and exchange between the respective disciplines and also of the personal knowledge of the collaborating scientists. Often important input comes from a completely unexpected direction. As the creation of most archaeological phenomena was not scientifically motivated, rules and reasons for their existence can also be derived from other techniques including crafts and the arts. As they also reflect the purposes and demands of everyday life, a practical and straight forward interpretation is often more useful and evident than rather complicated scientific arguments. This is also reflected by the need for communication with the local communities and people, who often have knowledge of past land use. As an example the initially misinterpreted naming of a specific area in the Kreuttal region might serve here. The “Weinsteiger Viehdrift” (the name is indicated in old maps) was first interpreted as a cattle trail, also because of the local appearance of multiple medieval hollow path bundles. “Viehdrift” is an old local idiom for pasture and indicates that the people from the village Weinsteig kept cattle in this area (probably during warm seasons, which might also be indicated by the expression). This example also illustrates, how an evidence has been treated as correct (cattle trail), because it seemed to be trivial. Another discipline or also the communications with local people provide the missing information.

As the basic demand of multidisciplinary research is the collaboration of different disciplines, a basic knowledge of the theoretical framework of applied methods is crucial. It is more often a greater challenge for a scientist to pin down the results and their respective interpretation of his or her own discipline in such a way as to also reflect the demands of another discipline. This is especially complicated, when natural sciences and humanities must collaborate and discuss and compare their respective results. A long term discussion includes the absolute dating of the chronology observed in Tell el Daba. The chronology derived from humanistic sources should be correlated with the results gained through radiocarbon dating. Radiocarbon dates show a general offset of approx. 100 years compared to the archaeologically derived chronologies. Both methods lead to contradictive results regarding the absolute dating of specific archaeological phases. Although no consensus could yet be found, the discussions led to profound and critical methodological research in determining and detecting interfering parameters. In this lucky case, the results are expected to be correct from both groups of scientists. Although the contradiction has not thus far been able to be eliminated, both disciplines and respective methods have benefitted from these results (Kutschera et al. 2012).

This positive example of multidisciplinary work and treatment of contradictive results previously described, also illustrates possible pitfalls. If the hypothetical character of the interpretations based on the respective results had been neglected, a collaborative scientific discussion would have been impossible. It is understandable, if not scientifically so, if long term and well established theories seem to be falsified and need to be adapted. Whereas falsification is a practical theoretical concept for closed systems it is more complicated for open systems, which require the description and investigation of archaeological evidence. From this perspective a theory can be only falsified regarding the parameters already embedded. For the archaeological sciences and research it is therefore crucial to include contradictions as a basic positive principle of the given theoretical and practical framework. Contradictions must rather be looked for than avoided, because they signal the potential for the further optimization of applied techniques and the introduction of thus far unknown interfering parameters.

Multidisciplinary research is based on the exchange of messages between the disciplines involved. A message is not objective. If no common agreement regarding the type and appearance of a message is made by receiver and sender, it cannot be understood (Hofstadter 1986). This is especially tricky, when the differences are rather small, but have nevertheless great impact. For example, the stratigraphic sequence displaying the excavation process of a specific archaeological site can be described as “valid” regarding the physically and mathematically correct display of the spatial superposition of stratigraphic units. The expression “valid” could - within an archaeological context - also be related to the comparison of the stratigraphic sequence and the true stratification primary to excavation. It could be argued, whether the stratigraphic sequence is a valid representation of the true stratification. In this case “valid” is not the correct word and would be misunderstood, as the degree of representation is not clearly specifiable. The scientific communication of disciplines demands a fundamental knowledge of the theoretical framework of each single discipline and the willingness to accept basic theoretical and practical arguments and demands of the other disciplines. For the one, a strict focus on specific disciplinary rules and concepts is crucial, whereas for the other only an open minded approach fulfils these demands. Both concepts are important for the increase of scientific knowledge and both have respective shadows, namely narrow-mindedness and arbitrariness (Pietschmann 2009). Without correct and well-defined vocabulary, the communication of different scientific disciplines is difficult. Sometimes it is even hard to find a consensus on the used vocabulary, even within a single discipline. This is often the reason for the creation of new words and phrases, which are not scientifically and emotionally colored.

Finally the successful application of multidisciplinary research followed by integrated interpretation is dependent on a very subjective issue – the scientist and scientific institutions involved. The perception of each science is very individual and closely related to personal experience, knowledge and academic education. To answer research question in a multidisciplinary way, an equilibrium between the different disciplines must be found and optimized for the respective situation. Scientists must be open-minded regarding the results and theories of other disciplines but still be aware of the limits and validity of their own discipline in respect to a given topic of multidisciplinary research

(Pietschmann 2009). Although the temptation is high to benefit from derived results in combining different methods and theories too quickly, the reproducibility and comparability of theories and results is only guaranteed by obeying clearly defined routines exactly.

<u>PAPER #6:</u> Reading the past reading the data

<u>Preamble</u>

This paper was originally presented as a dialogue between an archaeologist and a physicist. It aims to discuss the basic principles and theoretical framework of humanities and natural sciences. As this is also a main aspect examined within this thesis the paper discusses also basic differences but also similarities of sciences. The provenience of archeological material is compared to properties and characteristics of datasets analyzed in natural sciences.

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Abstract

This paper aims to show that there is an epistemological process common to all sciences. In particular, scientific thought in physics and archaeology will be compared to demonstrate the existing similarities. Based on a set of data and the application of a specific method, theories and interpretations are derived and become subjects of academic debates. In an archaeological context, this requires to clearly define the above concepts. To clarify the nature of the archaeological data set, a model of the formation of an archaeological “find” or “feature” is presented. It is shown that the data set is defined by both human (subjective reality) and natural (objective reality) factors during its formation and documentation. All methods applied to the data set to arrive at an interpretation must be fully disclosed to facilitate future scientific debates of results. Only this allows for reproducible and comparable conclusions.

Introduction and Motivation

We assume that all sciences are based upon common epistemologies. Therefore it seems useful to compare the theoretical and practical approaches of different sciences in gaining knowlegde. Especially archaeological sciences, commonly understood as a part of the humanities, have been criticized for not being as exact and well defined as e.g. physics. At this point we find it necessary to analyse whether physics truly is an exact science or not. In physics the database is interpreted using well defined methods. Interpretations and results have to be reproducible and comprehensible. Physics requires strict methods for working on this data set, otherwise, its results cannot be exact. But it is a fact that the act of producing the data set by measurements influences the primary data (Pietschmann 1996). In quantum mechanics it is widely accepted that the measurement itself produces the particular state of the particle (Zeilinger 2005; Meißner 1992). To compare results embedded in physical theories it is necessary to keep in mind that this is only possible within a certain and declared frame of reference In quantum mechanics the philosophical idea of determinism had to be abandoned, although many scientists are still longing for it. To summarize, in physics it is not the data set itself that is strict, but the methods of producing and dealing with the data set are of common, well defined and declared nature. It is obvious that if the methods of dealing with an archaeological data set also are of common, well defined nature, then there is no difference in the accuracy of physics and archaeology. Thus, we want to take a closer look at the archaeological data set.

The archaeological data set

First of all, it is necessary to define the character of the archaeological data set. As determining its structure directly is very difficult, we want to embed the data set within the description of where it originates from, how it is produced, deposited and documented. In doing so it is possible to separate three phases as shown in Figure 64.

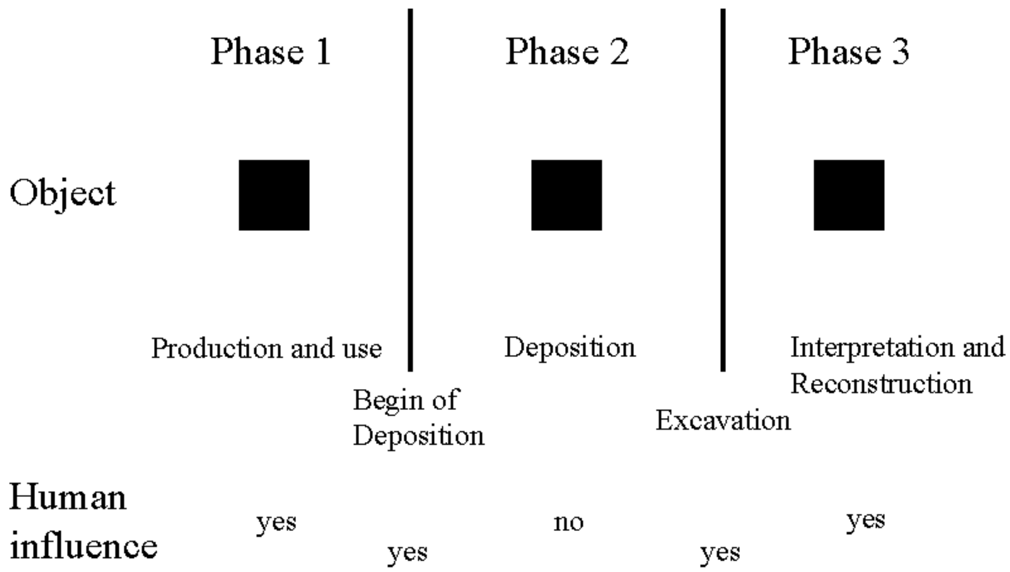

Figure 64: Life history of an artefact or archaeological feature (© M.Kucera).

In Phase 1 an archaeological artefacts or features are produced and used. The Phase of deposition (Phase 2) starts with the deposition itself and ends with the excavation of the object. The interpretation and reconstruction of the circumstances of production and use of archaeological artefacts or features take place in phase three. It is obvious that human influence is guaranteed through all phases except phase 2, assuming that the object remains undisturbed. For a precise description of these three phases the difference of subjective and objective reality (Wirklichkeit and Realität) has to be illustrated first. The sciences investigate objective reality. E.g. in physics, general laws should characterize nature, both of which are seen as objective. Subjective reality is formed by every human being depending on individually perceived experiences, social life and environment (Pietschmann 1990). Imagine that we swim in a lake of subjective reality where the bottom of the lake is the objective reality we want to observe. It is not easy to describe the bottom of the lake, but with special equipment (snorkel mask) and laws to calculate the refraction of light, we are able to find a close description of it. To make our results reproducible and traceable, we need to tell all the other swimmers that we have used a snorkel mask and the law of refraction to calculate the bottom. On Figure 65, subjective and objective realities are connected with the postulated three phases (compare also (Kucera 2004).

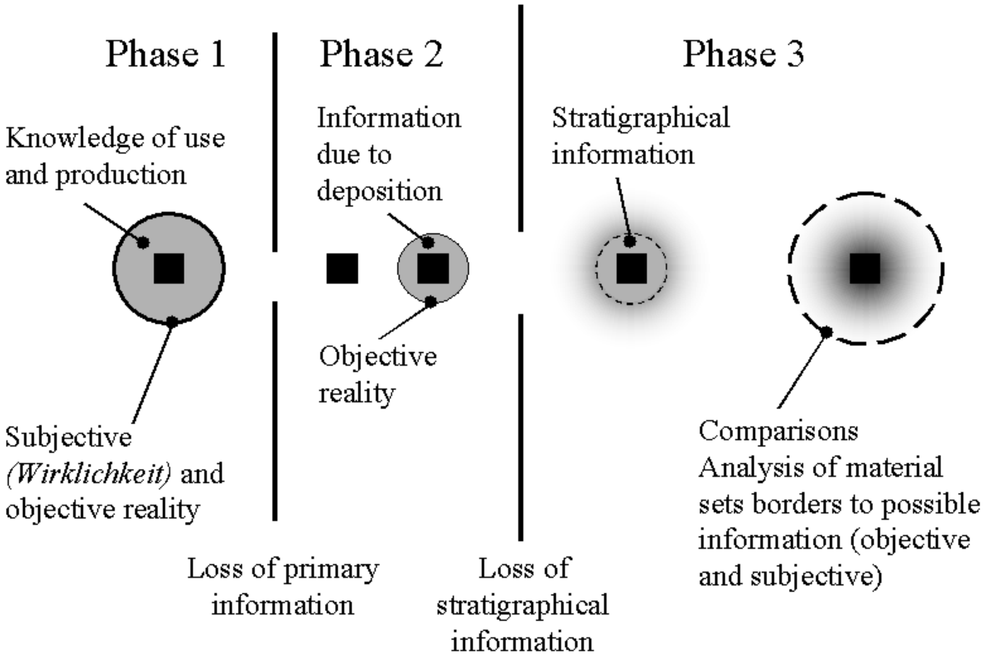

Figure 65: Changes of the information associated with an artefact or archaeological feature (©M.Kucera).

Phase 1 shows the influence of both factors on an archaeological object. It is obvious that production and use of an object is linked to and limited by physical factors, e.g. the sites of fracture within flint stone, and subjective factors such as tradition, culture and other necessities of life. Therefore we can set a borderline defined by subjective and objective reality to the production and use of an archaeological object. During phase 1, all necessary information about an object is generally known, knowledge quickly lost after its deposition. One might say that the object has left the human sphere. During deposition information is built up again due to physical factors (objective reality) following the laws of stratigraphy. An excavation being an experiment only possible to be made once destroys the stratigraphy which was built up from the time of deposition to the time of the excavation itself. We are able to reconstruct parts of the stratigraphic information by using well defined methods for interpretation as shown in Phase 3. Again methods like comparing artefacts with other archaeological sites, analysis of materials and others allow defining parts of the original borderline composited of subjective and objective reality. It is a fact that the status of phase 1 – all necessary information about an object being known – is irretrievable. This at least partially is also due to personal methodical preferences of individual scientists. As these preferences are subjective, they are linked to subjective reality, but by declaring the methods used for interpreting an archaeological data set, results and interpretations become reproducible, traceable and thus objective (Schülein and

Reitze 2002).To summarize, the archaeological data set can be defined as a composite of subjective and objective reality and - like in any other science – has to be interpreted accordingly.

Interpretation in Archaeology

After this assessment of the nature of an archaeological data set we want to discuss phase 3, its interpretation. This phase consists of three sub-phases which comprise of a pre-interpretative, an interpretative and a post-interpretative stage. The pre-interpretative stage means collecting the data which in archaeology usually consists of excavating. The excavation process itself however is also interpretative. Excavating implies the search for stratigraphic units, their borders, dimensions and topography (Wheeler 1954; Harris 1979). At that point archaeology is very similar to quantum physics: The observer (excavator) produces the particular state of the observed stratigraphic unit by excavating. During the process of excavation we want to find the precise borders, dimensions and topography of such a unit. In fact it is impossible to precisely reproduce these states. But it is - within a certain range – the closest approach to the original stratigraphic unit to be defined. In that way excavating is an interpretative act. The next step in the field would be to document the interpretatively defined stratigraphic units, which is usually achieved with sufficiently great accuracy and thus does not introduce additional errors to the data. We understand that excavating is an experiment viable only once. Therefore it must use common, well defined and declared excavation and documentation methods which result in comparability and reproducibility. Finally preparing the data – like cleaning finds, sequencing units of stratification or ordering the documentation - concludes the pre-interpretative phase. The character of an excavation and its documentation has to be accepted to be interpretative. A discussion of this "stratigraphic interpretation" should deal with the observation and development of methods, not with the particular contents of the specific interpretation, with the latter being part of a second stage of academic debate. Thus, archaeological research aims to reconstruct past subjective and objective reality based on a primary interpretative data set, which has to be interpreted again in a second stage of the archaeological process, which we would like to call the interpretative stage.

The first step of this stage is the phasing of the stratigraphic sequence by analysing finds and scientific dating. Then the actual interpretation of the data takes place. Information from the phased sequence and all other analyses of the data set along with comparisons of the results from other sites are combined in a comprehensive interpretation of the past subjective and objective reality of the investigated site. This interpretation usually is incorporated in site reports, papers or other forms of archaeological publication. These interpretations can lead to new archaeological theories as approaches to the past objective reality.

In the final post-interpretative stage the interpretations have to be discussed by the scientific community by means of reflections, reviews and other forms of communication. The interpretative and post-interpretative phases are to be understood as a hermeneutic spiral. The interpretation has to be discussed and analysed and the newly found information has to be incorporated back into the original interpretation.

Conclusion and Solution

Archaeology can be as accurate as physics if archaeology uses common, well defined and declared methods of excavation and documentation to get a data set to work with. Otherwise interpreting the data is difficult or impossible. The archaeological database is embedded in subjective and objective reality in the past as well as in the present. An excavation which is needed for collecting archaeological data is an interpretative act by its very nature.

If reading the past means reading the data, the process of gathering the data and interpreting has to be made as transparent as possible. In order to guarantee reproducibility, traceability and comparability the used methods have to be communicated and possible errors must be revealed. Once common methods are defined and declared constructive discussion on archaeological interpretations and results can take place. Therefore it is necessary to separate discussions on methods from discussions of results.

PAPER #7: Der Dämon der Interdisziplinarität

Preamble

This paper has also to be seen as a kind of introduction to the conclusion of this thesis. Whether and under which circumstances interdisciplinary scientific work is possible, is discussed within the paper. It displays also personal experiences regarding the benefits and pitfalls of interdisciplinary work and communication.

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Abstract

In respect to the application of multiple methods derived from various scientific disciplines most of archaeological research can be unified under the paradigm of multidisciplinarity. The communication between different disciplines combined with the knowledge of their specific functionality and theoretical and methodological framework is crucial for an effective collaboration, with the aim to publish reproducible results and archaeological theories. For this purpose the nature of the necessary theoretical framework should be analyzed to fulfill the demands of interdisciplinarity. Different scientific approaches especially of humanities and natural sciences might cause misinterpretation of given data and theories. Whereas the separation of concepts to derive knowledge into clearly defined disciplines was and still is a necessary and productive step, it appears that this separation also causes problems within interdisciplinary investigations nowadays. In this sense this separation is both - a very powerful tool but also limiting possibilities for further knowledge.

Einleitung

Wie jede Wissenschaft erfahren auch die archäologischen Wissenschaften mit jeder weiteren Generation eine neue Orientierung und Definition ihrer potentiellen Aussagemöglichkeiten und wissenschaftlichen Fragestellungen. Letztendlich bleibt die Frage, wie die Archäologie im Allgemeinen beabsichtigt, Erkenntnisse über ihr Forschungsobjekt zu erlangen. Dazu gilt es vorerst, dieses Forschungsobjekt und das Forschungsziel zu definieren. Es herrscht weitest gehend Konsens darüber, dass die Archäologie in der Analyse der materiellen Hinterlassenschaften der Menschheit versucht, den Menschen, aber auch seine Umwelt, im Wandel der Zeit zu untersuchen und zu verstehen. Während die Frage nach der wissenschaftlichen Absicht der Archäologie relativ klar zu beantworten scheint, ist eine Darlegung eines wohl definierten Erkenntnisfindungsprozesses um einiges komplexer. Wie sich Wissenschaft generell definiert und verortet, wie sie auch vergleichbar ist mit der Kunst (Feyerabend 1983), ist selbst in der Wissenschaftstheorie umstritten bzw. wird dies sogar oft in Diskussionen ausgeklammert. Hingegen erscheint es sinnvoll, Wissenschaften anhand der von ihnen angewandten Methoden zu definieren (Kuhn 1973; Chalmers and Bergemann 2001). Bezogen auf die Archäologie hieße das, im Sinne einer entsprechenden Grundlagenforschung, die Methoden der Archäologie zu hinterfragen und klar zu definieren. Ein schneller Blick legt die Vermutung nahe, dass die Archäologie eine Vielzahl an Methoden kennt und auch äußerst erfolgreich einsetzt. Die Entwicklungen der letzten Jahrzehnte haben gezeigt, dass nahezu alle Wissenschaften – aber auch Künste und Handwerke – für die Beantwortung archäologischer Fragestellungen Relevanz haben. So kommen Disziplinen, die sich unterschiedlichster Denkmodelle bedienen, zum Einsatz. Wie kann nun eine Kommunikation zwischen diesen Disziplinen stattfinden? Was bedeutet es, wenn Daten auf Argumente treffen? Was sind die Kernfragen zur Frage nach der prinzipiellen Möglichkeit, in einen interdisziplinären Disput zu treten? Liegt in der Beantwortung dieser Fragen vielleicht auch das Potential zur Beantwortung grundlegender erkenntnistheoretischer Konzepte?

Es mag für die Beantwortung konkreter archäologischer Überlegungen nicht von Bedeutung sein, diese Fragen zu analysieren. Die Nachvollziehbarkeit archäologischer Aussagen für nachfolgende Generationen ist allerdings nur gewährleistet, wenn auch diese Aspekte im Sinne einer archäologischen Grundlagenforschung erwogen und geklärt werden. In diesem Licht sind die folgenden Erwägungen zur Möglichkeit und Unmöglichkeit interdisziplinären Arbeitens und Forschens in der Archäologie zu verstehen.

Archäologische Disziplinen – verschiedene Denkmodelle

Die rasante Entwicklung technischer Möglichkeiten der letzten Jahrzehnte hat das Spektrum des Einsatzes vielfältigster Methoden aus nahezu allen Bereichen der Wissenschaft in der Archäologie ermöglicht. Während Archäologie traditionell mit Grabungswerkzeug und dem Literaturstudium in Bibliotheken verknüpft wurde, hat sich das Anforderungsprofil hin zu einem Wissenschaftlertyp entwickelt, der im Prinzip alle Disziplinen in sich vereinen sollte. Ist es schon oft schwer, einen konstruktiven wissenschaftlichen Disput zweier Spezialgebiete innerhalb einer Disziplin zu führen, erweist sich das bei unterschiedlichen Disziplinen als umso komplexer. In diesem Zusammenhang sei auf unterschiedliche Denkmodelle beziehungsweise auch Denkmuster einzelner Disziplinen hingewiesen. Besonders gravierend wird der Unterschied zwischen geisteswissenschaftlichen und naturwissenschaftlichen Denkansätzen sichtbar. Während tendenziell die einen auf Argumente angewiesen sind, arbeiten die anderen mit Daten. Einen besonderen Einfluss auf das Verständnis für die Funktionsweise und Charakteristik der jeweiligen Disziplin hat auch die je nach Betrachtungswinkel variierende Wahrnehmung einer bestimmten Disziplin aus der Perspektive einer anderen. Als Beispiel möge hier die Wahrnehmung der Physik als exakte Wissenschaft dienen – eine Annahme, die für die meisten Physiker unverständlich ist. Im Selbstverständnis eines Physikers beschreiben physikalische Theorien beobachtete Effekte im Rahmen des Messfehlers – abgesehen davon, dass Messungen durch die bloße Anwesenheit von Messinstrumenten beeinflusst werden. Zusätzlich sind diese Theorien immer als Konjunktiv zu verstehen und nur so lange gültig, wie sie keinen beobachteten Phänomenen widersprechen. In der Physik werden diese Phänomene durch Experimente gemäß der experimentellen Methode sichtbar gemacht. Wollte man diesen Vorgang mathematisch formulieren, so wäre die Methode eine Funktion, die ein Phänomen in einem wissenschaftlichen Kontext abbildet. Mit archäologischen Phänomenen verhält es sich ähnlich, wobei prinzipiell die Wahl der Methode die Art der Abbildung beeinflusst und bedingt. Es sei darauf hingewiesen, dass es keinen Unterschied für diese Überlegung macht, ob es sich dabei um eine naturwissenschaftliche oder geisteswissenschaftliche Methode handelt. Dies macht deutlich, dass erstens außer der Selbstkenntnis der einzelnen Methode im Kontext einer Disziplin auch die „Fremdkenntnis“, also das, was von ihr aus dem Blickwinkel einer anderen Disziplin oder Denkschule erwartet wird, nötig ist. Zweitens muss die angewandte Methode klar definiert sein, um eine eindeutige Zuweisung einer Abbildung an ein beobachtetes Phänomen nachvollziehbar zu machen. Im nächsten Schritt kann diese spezielle Abbildung in einem größeren Kontext mit anderen Abbildungen verglichen und interpretiert werden und als Basis und Bestätigung einer vorläufig angenommenen (archäologischen) Theorie dienen.

Ohne an dieser Stelle darauf einzugehen, ob es sich hierbei um interdisziplinäres Arbeiten handelt, ist dieser Vorgang durch eine klare Abgrenzung der Disziplinen zueinander charakterisiert. Diese Abgrenzung erlaubt den Gültigkeitsbereich spezieller Aussagen zu definieren, vor allem wenn die Abbildungen eines Phänomens, auf das unterschiedliche Methoden angewandt wurden, im Widerspruch zu stehen scheinen. Um dies zu illustrieren nehmen wir an, dass auf einer Ausgrabung eine ungestörte Bestattung mit einem Schwert als Beigabe gefunden wird. Im Sinne einer traditionellen archäologischen Wertevorstellung wird dieses Grab daraufhin als „Männergrab“ identifiziert, wobei die archäologische Methode der Analogie zum Einsatz kommt. Eine anthropologische Untersuchung ergibt nun eine Bestimmung des biologischen Geschlechts als signifikant weiblich. Es gibt nun die Möglichkeit, beide Methoden in Zweifel zu stellen oder den Methodenkanon um eine weitere Methode zu erweitern, um den Widerspruch zu erklären und ein soziales Geschlecht zu definieren. Dieses Beispiel führt auch klar vor Augen, wie gerade in der Archäologie der scheinbare Widerspruch Erkenntnis erweitern kann und demzufolge nachgerade gesucht werden muss. Ein Widerspruch ist aber nur zu finden, wenn zwei oder mehr Aussagen nachvollziehbar gegenübergestellt werden können, was wiederum eine genaue Kenntnis der angewandten Methodik, sowie deren Aussagenzulässigkeit, voraussetzt. Mit Aussagenzulässigkeit ist in diesem Zusammenhang gemeint, was eine Methode an Aussagen prinzipiell erlaubt und ermöglicht. So sagt ein dendrochronologisches Datum aus, wann ein Baum gefällt wurde, nicht aber wann er beispielweise in ein Haus eingebaut wurde. In diesem Fall erscheint die Aussage trivial, ist jedoch in komplexeren Systemen oft Ursache für scheinbare Widersprüche.

Schatten der Interdisziplinarität

Es zeigt sich, dass die Archäologie auf andere Disziplinen angewiesen ist, um ihr Potential zur Erkenntnisfindung weiter auszuschöpfen. Bevor bereits mögliche Resultate der Anwendung dieser verschiedenen Disziplinen und ihre Gültigkeit und Wertigkeit diskutiert werden können, mögen Gedanken hilfreich sein, die die primären Bedingungen und Abhängigkeiten bei der Verknüpfung einzelner Disziplinen hinterfragen. Vereinfacht ausgedrückt kann man auch fragen, welche Rahmenbedingungen gegeben sein müssten, um interdisziplinäres Arbeiten zu ermöglichen und wie in diesem Zusammenhang mit widersprüchlichen Aussagen umzugehen ist. Daher ist eine kurze Betrachtung des Wesens von Widersprüchen innerhalb eines wissenschaftlichen Kontextes nahe liegend.

Herbert Pietschmann hat in zahlreichen Arbeiten zum (natur-)wissenschaftlichen Denken auf die Diskrepanz von aristotelischem Denken, dem Auftreten von Widersprüchen und mit deren Umgang im Sinne einer Dialektik hingewiesen. Er zeigt deutlich, dass das wissenschaftliche Denken abendländischer Tradition von den drei Axiomen der aristotelischen Logik geprägt ist. Gerade das dritte Axiom (vom ausgeschlossenen Dritten – *tertium non datur*) zwingt zur Entscheidung zwischen zwei widersprüchlichen Aussagen. Vor allem beeinflusst durch die Schwierigkeit der Widersprüchlichkeit innerhalb der Quantenmechanik, versucht Pietschmann ein Bild einer angewandten Dialektik zu zeichnen, die es erlaubt, konstruktiv mit dem Widerspruch in den Wissenschaften umzugehen (Pietschmann 1996). Zur Erklärung verweist er unter anderem auf die Existenz von polaren Begriffspaaren (z.B.: unterscheiden – vereinen), die eigentlich nicht im Widerspruch stehen, ihre sogenannten Schatten (trennen – egalisieren) aber schon. Zieht man Beispiele aus der Alltagserfahrung heran, wird der zugrunde liegende Mechanismus deutlich. Eine Gruppe von Menschen mag Vereinigung anstreben und Unterscheidung – so notwendig sie auch empfunden werden mag – aus Angst vor der Trennung ablehnen. Der Widerspruch besteht nicht im „unterscheiden“ sondern in der Dominanz seines Schattens „trennen“ (Pietschmann 2009).

Legt man diese Gedanken auf den Einsatz verschiedener Disziplinen und auf das, was dieser erfordert, um, so kann das polare Paar „fokussiert“ und „offen“ gefunden werden. Beides sind Eigenschaften, wie man sie durchaus von jedem Wissenschaftler erwartet. Deren Schatten sind aber „eingeschränkt“ und „beliebig“, was veranschaulicht, worin Vorbehalte gegenüber dem Einsatz von Methoden verschiedener Disziplinen begründet sein können. Je fokussierter an einem Problem gearbeitet wird, desto fundiertere Ergebnisse sind zu erwarten, allerdings besteht die Gefahr, dass die Gesamtsicht verloren geht. Andererseits können bei allzu großer Offenheit Ergebnisse als zu beliebig betrachtet werden. Dieser Zustand ist eine Aporie, die nur in einer Synthese aufzulösen ist, der beide Seiten zustimmen und mit der Neuland betreten wird (Pietschmann 2009). Diese Forderung ist auch auf die Resultate selbst erweiterbar, in dem Sinne, dass der existierende Widerspruch in einem übergeordneten Gedankenmodell aufgelöst wird, ohne den ursprünglichen Kontext in Hinsicht auf die Nachvollziehbarkeit zu vergessen. Eine Voraussetzung ist hierbei eine klare methodendifferenzierte Definition der jeweiligen Disziplin, auch um die Disziplinen in ihrem Unterschied zueinander zu charakterisieren und die daraus resultierenden Vorteile, aber auch Schwächen, zu analysieren.

Aristotelischer Dämon

Betrachtet man typische archäologische Fragestellungen und versucht, ein gemeinsames Charakteristikum zu finden, so sind das wohl die Multikausalität und der Umstand, dass jegliches archäologische System als offenes System zu betrachten ist. Wollte man die Wissenschaft als Werkzeug auffassen, so wäre das Werkzeug der Wahl eines, mit dem man alles machen kann, auch das, von dem man noch gar nicht weiß, was man machen wird müssen. Da es das nicht gibt, ist man darauf angewiesen, das Gesamtproblem in einzelne Fragestellungen zu zerlegen, diese mit unterschiedlichen Methoden zu analysieren, um abschließend das, was zerlegt wurde, wieder zusammenzusetzen und in den meisten Fällen basierend auf den gewonnen Erkenntnissen in ein größeren Zusammenhang zu setzen. Hier stellt sich die Frage, inwieweit das möglich ist. In diesem Kontext soll der Begriff des „aristotelischen Dämons“ eingeführt werden. „Dämon“ ist hierbei im ursprünglichen durchaus doppeldeutigen Sinn des griechischen *δαίμων* als etwas Glückverheißendes aber auch Unheilvolles zu verstehen. Der Bezug auf Aristoteles beruht auf der ihm oft zugewiesenen Rolle als einem der ersten, der die unterschiedlichen Wissenschaften definiert hat. Diese Unterteilung erwies sich als ein Erfolgsmodell, das sich schließlich in der Neuzeit fortgesetzt hat und, neben der aristotelischen Logik selbst, das wissenschaftliche Denken bis heute prägt. Das ist die positive Komponente der Trennung der einzelnen Wissenschaften voneinander. Letztendlich liegt aber genau in dieser Trennung das Dilemma des interdisziplinären Arbeitens, dessen Kernaufgabe es zu sein scheint, das was getrennt wurde, wieder zusammenzuführen. Ein kurzer Blick auf das bereits erwähnte polare Paar „unterscheiden“ und „vereinen“ zeigt hier deutlich die Gefahr der Schatten „trennen“ und „egalisieren“. In dem Maß, in dem die angewandten Disziplinen zu unterscheiden sind, sind ihre Ergebnisse zu vereinen. Je klarer hierbei die Unterscheidung ist, desto deutlicher, inhaltsreicher und nachvollziehbarer sind die Ergebnisse einzelner Methoden zusammenzufassen. Je klarer diese Unterscheidung ist, desto mehr wird auch ein weiterer Schatten unterdrückt, jener der Beliebigkeit.

Conclusio

Der Begriff der Interdisziplinarität ist in den letzten Jahrzehnten generell diskutiert worden, nicht nur hinsichtlich seiner Definition, sondern auch in Hinblick auf praktische Anleitungen zum effektiven wissenschaftlichen Arbeiten. Von allen Wissenschaften scheint sich die Notwendigkeit echten interdisziplinären Arbeitens in der Archäologie am systemimmanentesten zu zeigen. Wie kaum eine andere Wissenschaft braucht sie gemäß ihrer Forschungsabsicht eine größtmögliche Anzahl an Disziplinen, die innerhalb eines archäologischen Kontextes angewandt, zum weiteren und vertiefenden Verständnis klar definierter Fragestellungen beitragen können. Im Sinne eines „Unterscheide, ohne zu trennen“ (Pietschmann 2009) ist es dafür nötig, eingesetzte Disziplinen hinsichtlich der Aussagenzulässigkeit ihrer Methoden klar voneinander zu unterscheiden. Sie nicht zu trennen, erlaubt das Wissen um die Selbstkenntnis wie auch die Fremdkenntnis der angewandten Disziplinen. Das wiederum setzt die Notwendigkeit eines fundierten wissenschaftlichen Disputes einzelner Fachdisziplinen voraus, wobei die einzelnen Protagonisten zwar Experten in spezifischen Gebieten sein müssen – um die Beliebigkeit auszuschließen – allerdings auch Kenntnisse besitzen, die benachbarten Disziplinen ihrer systeminternen Logik gemäß einzuordnen. Die Bewertung des jeweiligen Methodenkanons erfolgt somit im interdisziplinären Dialog der Wissenschaften und Disziplinen. Ein wohldefinierter Methodenkanon, basierend auf den fachspezifischen Anschauungen der jeweiligen Disziplinen, angewandt auf eine klar definierte archäologische Fragestellung, ist die Basis für die Nachvollziehbarkeit der Ergebnisse. Um dies zu gewährleisten sind drei Grundvoraussetzungen axiomatischen Charakters zu erfüllen. Erstens muss die Aussagenzulässigkeit für eine konkrete archäologische Fragestellung einer bestimmten Disziplin von einem / einer fachspezifisch ausgebildeten WissenschaftlerIn beurteilt werden, der / die allerdings mit grundlegenden Mechanismen archäologischer Denkweise vertraut ist. Zweitens bedarf es eines archäologisch ausgebildeten Gegenübers, von dem aber außer der spezifischen Fachkenntnis auch Wissen um mögliche Methoden zur Erforschung einer im Vorhinein definierten Fragestellung gefordert wird. Das zu gewährleisten, ist eine große Aufgabe und Verantwortung der archäologischen Ausbildung, die ein höchstes Maß an kritischer Beurteilungsfähigkeit und grundlegende Kenntnisse über die prinzipielle Struktur von Erkenntnisfindungsprozessen in der Wissenschaft im allgemeinen sowie in einzelnen Disziplinen im speziellen voraussetzt. In diesem Lichte ist eine tiefgreifende Diskussion über die Grundlagen der Archäologie notwendig. Im eigentlichen Sinne einer Grundlagenforschung sind die angewandten Methoden, ihre Verknüpfung gemäß den disziplinenspezifischen Regeln bis hin zum jeweilig eingesetzten Methodenkanon mit klar definierten Aussagenzulässigkeiten kritisch zu hinterfragen und im interdisziplinären Dialog zu diskutieren. Dieser Vorgang führt zum dritten und wichtigsten Punkt – der Kommunikation der einzelnen Disziplinen. Grundlegend dafür ist durch Analyse der Selbstkenntnis und Fremdkenntnis gleichsam ein Vokabular zu entwickeln, das uns erlaubt, die Sprache der Interdisziplinarität zu sprechen. In diesem Sinne ist auch der Dämon der Interdisziplinarität als Metapher zu verstehen. Erst wenn ich meine Dämonen kenne und verstehe, können sie mir nützlich sein.

Danksagung

Ich freue mich sehr Herrn Prof. Falko Daim mit diesem kurzen Artikel meinen Dank und meine Hochachtung für seine persönliche Unterstützung auszudrücken. Sein Einsatz, sowohl in der Forschung als auch in der Lehre, die Möglichkeiten des interdisziplinären Arbeitens in der Archäologie zu erkennen, zu fördern und voranzutreiben, ist ein wesentlicher Teil des Fundamentes der modernen archäologischen Wissenschaften.

Conclusions

Multidisciplinary research and archaeometry

Within this thesis results on different levels are presented and discussed. Various examples of the application of archaeometric methodology illustrate the multidisciplinary aspect of archaeological research. Application examples of SEM and pXRF for analytical material analysis display the huge variety of the physical and chemical properties of archaeological material including artifacts, ecofacts and soil. Exemplarily for near-surface geophysical prospection, magnetic prospection and its respective hardware and methodological development have been discussed. Additionally other geophysical methods - namely resistivity surveys, electromagnetic surveys and ground penetrating radar - have been explained in order to characterize the physical properties, mainly relevant for the detection of archaeological evidence. These are permittivity, resistivity and permeability. Results of each of these methods, originating from different disciplines, have been presented. A main focus was set hereby to guarantee well-defined data acquisition and processing procedures. Therefore results have to be concluded separated by results achieved through monodisciplinary and multidisciplinary research (Parthey 2011).

Monodisciplinary results

SEM surface analysis for the documentation of dental calculus was utilized to control the amount of impact of the dental wash technique (introduced by (Boyadjian et al. 2007) on the specimen. This was done to derive best practice suggestions for the dental wash technique. A main emphasis was set on the clear description of benefits and limits of the respective methodology (pp.78).

The second work regarding the usage of SEM for archaeological purposes, displays the huge variety of different applications of this methodology. It illustrates the importance of documenting the derivation of respective analytical information. Although detection limits are comparably high, the combination of image representation and chemical analysis using EDX is crucial for the detailed analysis and documentation of artifacts and biofacts (pp. 61).

The in situ application of pXRF results in the need for standardized sampling strategies. In a first step an analysis was done as to which degree on site pXRF analysis allows classifying different stratigraphic units based on their material component. In this respect general demands of accuracy and precision of applied techniques have been discussed in comparison to the character of archaeological material and contexts (pp. 92).

Since 2010 the LBI ArchPro has developed and optimized motorized magnetic prospection. For this purpose, standard routines for data acquisition (including field logistics, survey strategies and recording of metadata) and data processing were introduced and tested. This resulted in well-defined methodological workflow to guarantee the comparability and reproducibility of the results (157).

Multidisciplinary results

A challenge for the creation of an optimized and possibly standardized workflow for the overall interpretation of these monodisciplinary results is the decision when they should be interpreted through an integrative approach. As soon as reproducible results are derived from each methodological approach, they can be compared and interpreted regarding their archaeological relevance and context. As a commonality for most of these data is that they can be identified by a geographic location, the introduction of G-AIS is very useful to guarantee the reproducibility of respective results. It mainly supports the integrated interpretation of multiple datasets derived by multidisciplinary methodology. Data are managed, archived and visualized to support the spatio-temporal analysis of observed phenomena. The practical setup of G-AIS to manage and analyze legacy datasets has been illustrated by a G-AIS developed for the analysis of the excavation data from Tell el Daba (pp. 134). Aspects regarding the manifold opportunities gained through the integrated interpretation of multiple datasets, are given by the description of the results of the LBI ArchPro case study Kreuttal (pp. 157).

Especially to display the temporal aspects of archaeological evidence, basic theoretical concepts regarding temporal synchronization and sequencing were introduced and discussed. In this respect an interval based approach (Allen 1983) for the synchronization of events and the resulting possible superimposition of time intervals can partly replace models dealing with single moments in time and the basic temporal relations “earlier, later and contemporary” (Drap et al. 2017). Weighting of presumed temporal sequences and time intervals is possible and demanding (Crema et al. 2010). Models to demonstrate the propagation of diseases biased by various factors (Silva 2016) can be also used to investigate the distribution of artifacts and information. In order to mathematically solve these relations, a fundamental model based on time cubes has shown promise (Crema et al. 2010). For this purpose each archaeological event or phenomenon can be related to a spatio-temporal entity.

Multidisciplinarity vs. Interdisciplinarity

Archaeological research is characterized by the application of methods derived from different disciplines. These disciplines cover a wide range of sciences from humanities and natural sciences. Collaborations of these disciplines have proven to be fruitful for archaeology and the respective disciplines as well. As the focus of archaeological research is dealing with an open system, which interacts with a socially and physically determined environment the interaction of multiple disciplines is crucial (compare also (Shahack-Gross 2017). Once well-defined routines of single disciplines and their respective reliability for a specific archaeological context are declared, respective results can be combined and compared. In this respect it is important to clarify in which way this is done in order to guarantee the reproducibility of the results (see also pp. 203).

In general multidisciplinary and interdisciplinary approaches can be distinguished, although borders between them are fuzzy in everyday scientific work. Within multidisciplinary research all applied disciplines work in parallel on different aspects of a given research question. The creation of a superordinate theoretical and practical framework is not pursued. This approach has been discussed especially in health sciences and health care, as regards its benefits and limits(Fawcett 2013). Health care can be characterized by its huge degree of complexity (Plsek and Greenhalgh 2001), which can be compared to archaeological research topics.

Interdisciplinarity is the interactive combination of the theoretical and practical framework of two or more disciplines optimized for a specific research question. Throughout this interdisciplinary work a partly complete new “interdiscipline” can be created reflecting the specific demands of a methodological framework. It is the basic challenge to overcome disciplinary specific framework towards an open-minded but not defocused implementation and reorganization within an interdiscipline. This has to be based on an interdisciplinary communication according to specifically defined vocabulary. In this respect it could be argued that interdisciplinarity is a science on its own (compare also (Bauer 1990).

Both concepts demand the constructive communication of the collaborating disciplines and scientists. They are capable of dissolving a given scientific context by defining different aspects, which can be analyzed by the respective disciplines or within an interdisciplinary approach. Especially interdisciplinary research seems to include a very personal and therefor subjective component.

The interdisciplinary scientist in archaeology

Each step within an integrative data interpretation approach of multiple datasets is characterized by specific demands for the respective scientist. This is a sometimes overwhelming challenge, as it demands broad as well as detailed knowledge. Personally I would like to illustrate this fact with the depiction of a diver found in the necropolis of Paestum/ Italy (Figure 66). The depiction is interpreted showing the transition between life and death. Somehow the diver appears very motivated and trustful, also because he is aware of his skills. Nevertheless, he cannot be sure of the outcome, when he enters the water.

Figure 66: The depiction of a diver found in the necropolis of Paestum/ Italy (©Heinz-Josef Lücking, CC BY-SA 3.0 de, https://commons.wikimedia.org/w/index.php?curid=33119457).

On the other hand only an open-minded approach based on the fundamental knowledge of different disciplines is able to derive further knowledge. Recently Hendrik J. Bruins gave a talk on new results regarding the detection of traces of a tsunami related to the Minoan eruption of the Santorini volcano (Bruins et al. 2008).[47] Although the presence of a tsunami was postulated nearly 70 years earlier (Marinatos 1939), he argued, that only the combination of archaeological and geological knowledge and methodology in terms of geoarchaeological surveying and analysis, allowed the detection of the respective evidence.

[47] The talk was held on the 8.6.2017 at the Institute for Isotope Research and Nuclear Physics/University of Vienna in Vienna.

A basic demand of multidisciplinary and interdisciplinary research is communication regarding the single scientists and the narrative being presented. For this purpose basic regulations and definitions for terms and phrases used by the respective sciences must be established in creating a vocabulary valid for interdisciplinary work (Izdebski et al. 2016).

Both aspects - the perception of scientific evidence and the communication of sciences – depend on the personal and subjective capabilities of involved persons. Furthermore the principle interdisciplinary competence of an individual is more likely representing his or her personal scientific socialization than skills adapted within an interdisciplinary research project. This specific socialization is related to academic educational systems and can be trained (Liebert 2013). Interdisciplinarity seems to be inherent to the global scientific system and cannot be created within a research project (Laitko 2011). This might be also the reason as to why interdisciplinary research is very personalized. If interdisciplinarity is inherent in science, the separation of disciplines is necessary to specify and analyze phenomena more precisely and is more artificial. On the one hand this separation guarantees an analytical approach; on the other hand it also limits respective results to a predefined context. Finally the perception of the theoretical and practical framework of one discipline from the point of view of another discipline might vary (see also pp. 209).

In this respect each scientist operating in the field of interdisciplinarity is responsible for a correct and understandable translation of results into respective narratives. The reproducibility of these results is gained through the application of well-defined methods within well-documented and possibly standardized procedures based on a common interdisciplinary vocabulary.

Outlook

When browsing in scientific papers and journals or monitoring current projects and scientific discussions, particular some words or phrases are often stressed. Whereas this has long been “interdisciplinary”, phrases dealing with “cultural heritage”,” innovative” or “open science” are nowadays apparent. Archaeology and archaeometry reflect most of these demands, as their major topic of research is cultural heritage. New methods have been developed to collect enormous amounts of archaeological data. Dealing with these data is one of the current challenges of archaeological research (Torrejón Valdelomar et al. 2016; Stadler and Kutschera 2005; Stadler 2014). The integrated interpretation of multidisciplinary datasets according to well-defined routines and the spatio-temporal analysis of the observed phenomena will be of constant interest. In particular, concepts derived from the demands of temporal sequencing of spatial entities are among the most challenging topics.

The general development of all sciences seems to evolve towards a multidisciplinary or even interdisciplinary approach. New media including social networks seem to provide a basic platform of scientific exchange. Information is available without almost no loss of time. It is becoming more and more possible to immediately compare different datasets and results worldwide. To guarantee the comparability of these datasets, it is crucial to rely on well-defined data management, processing and analysis tools.

In trying to describe both aspects of sciences, social and physical ones, the archaeological sciences best illustrate the current demands of all sciences. Strategies and methodologies developed to describe and solve archaeological research questions are suitable for a wide range of application. Through multidisciplinary or even interdisciplinary collaborations each involved discipline can benefit and new branches of science can be derived. Although archaeometry is basically used to analyze archaeological phenomena respective results and datasets also increase general knowledge and are placed at all sciences´ disposal.

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Abstract

Archaeology and archaeological sciences combine different disciplines to examine the spatial and temporal development of human societies based on material remains. The humanities and natural sciences provide a wide repertoire of disciplines and technologies for recording, analyzing, and interpreting archaeological evidence. Developing and applying multidisciplinary methods from this repertoire is essential for the documentation and preservation of archaeological heritage. Non-destructive methods of archaeological prospection reveal archaeological evidence at multiple scales from discrete phenomena to whole landscapes. Analytical sciences enable detailed analysis and dating of the material component of soil, artifacts, and ecofacts. Within this thesis, specific methods are presented: secondary electron microscopy (SEM), on-site application of portable x-ray fluorescence spectrometry (pXRF), and geophysical prospection, with the latter focusing on magnetic prospection. The analysis of results provided by various multidisciplinary methods demands an integrated interpretational workflow. This thesis suggests basic principles and routines to guarantee reproducible and comparable results, with the concept of acceptable threshold for scientific methods in *bona fide* archaeological conditions. A theoretical and practical framework for the spatio-temporal analysis of archaeological phenomena will be presented and discussed. The practical aspect involves the implementation of an archaeological information system (AIS), which is based on the functionality of geographic information systems (GIS). In order to fulfill the demands for integrated interpretation of archaeological data, AIS has to include various additional tools for temporal sequencing, data management, and data visualization. Clear definitions regarding the validity and limits of applied methods for specific scientific settings are crucial under these circumstances. This is argued within the discussion of the theoretical framework including limits and pitfalls of multidisciplinary and interdisciplinary research. For a valid integrated interpretation that is based on multidisciplinary approaches and is archaeologically relevant, data must be presented within a spatio-temporal context with room for both scientific and humanistic interpretations.

Zusammenfassung

Die Archäologie und die archäologischen Wissenschaften kombinieren verschiedene Wissenschaftsdisziplinen um die räumliche und zeitliche Entwicklung menschlicher Gesellschaften und Kulturen zu untersuchen. Die wesentlichen Informationsquellen sind die materiellen Hinterlassenschaften dieser Kulturen. Die Natur- und Geisteswissenschaften können auf ein großes Portfolio von verschiedenen Disziplinen und Techniken zurückgreifen, um diese Hinterlassenschaften erfassen, analysieren und interpretieren zu können. Für die Erhaltung und Dokumentation von archäologischem Kulturerbe ist die Entwicklung multidisziplinärer Methoden unerlässlich. Die zerstörungsfreien Methoden der archäologischen Prospektion erlauben das Auffinden dieser Hinterlassenschaften. Nicht nur einzelne Objekte sondern ganze Landschaften können so untersucht werden. Mit Hilfe der analytischen Wissenschaften können die Materialeigenschaften und auch das Alter von archäologischen Funden und Bodenproben bestimmt werden. In dieser Dissertation werden einige dieser Methoden behandelt: Rasterelektronenmikroskopie (SEM), der in situ Einsatz von Röntgenfluoreszenzspektrometrie (pXRF) und die geophysikalische Prospektion. Bei letzterem Thema wird vor allem auf die magnetische Prospektion eingegangen.

Die Analyse dieser auf multidisziplinärer Methodik beruhenden Ergebnisse erfordert einen integrierten Interpretationsablauf. Die vorliegende Arbeit versucht grundlegende Voraussetzungen und Abläufe der Dokumentation und Erkenntnisfindung zu untersuchen, die die Nachvollziehbarkeit der Ergebnisse gewährleisten können. Entscheidend ist dafür die Frage, welche Methoden für welche Fragestellungen und Aussagenbereiche Gültigkeit haben. In diesem Sinne werden praktische und theoretische Rahmenbedingungen erarbeitet und diskutiert, die die reproduzierbare räumliche und zeitliche Analyse archäologischer Inhalte ermöglichen. Praktisch können diese Voraussetzungen durch die Installation eines archäologischen Informationssystems (AIS) erreicht werden, das auf der Funktionalität von geographischen Informationssystemen (GIS) aufbaut. Für die integrierte Interpretation verschiedener archäologischer Datensätze muss ein AIS um zusätzliche Komponenten erweitert werden. Spezielle Anwendungen zur Visualisierung, Verwaltung und zeitlichen Sequenzierung erweitern die bestehende Funktionalität von GIS. Klare Definitionen der Aussagen- und Gültigkeitsbereiche der einzelnen Methoden auch in Hinblick auf einen diskret ausgesuchten Methodenkanon sind notwendig. Diese theoretischen Rahmenbedingungen werden im Kontext von multidisziplinärer und interdisziplinärer Forschung diskutiert. Damit eine gültige integrierte Interpretation, die auf multidisziplinären Forschungen beruht und archäologisch relevant sein soll, Gültigkeit hat, muss der räumliche und zeitliche Zusammenhang der Daten dargestellt werden und Platz für natur- und geisteswissenschaftliche Interpretationen bieten.

Curriculum vitae

Name

Mag. rer.nat. Matthias Kucera

Date and place of birth

3.2.1974, Vienna/Austria

Education

1980 – 1992	Primary school and grammar humanistic school BG III, Vienna, Austria
1992 – 2003	Studies of Physics, Philosophy, Pre- and Early History, Agyptology and classical Archaeology at the University of Vienna
2003	Mag. rer.nat., Physics
Since 2005	Interdisciplinary doctoral studies in Physics, Philosophy and Archaeology at the University of Vienna

Additional education

1998	workshop for ^{14}C-dating with AMS / University of Vienna
1998	workshop for geophysical prospection / University of Vienna
2003	workshop for Secondary Electron Microscopy / Company Zeiss
2005	workshop for Energy Dispersive X-ray Analysis (EDX) / Company Oxford
2006	workshop for Remote Sensing, RESPAL / University of Lubijana
2017	workshop ArcGIS online, ESRI/Austria

Employment History

Since 1996	staff member at various archaeological excavations
1997 – 2003	Collaborations at experimental archaeological reconstruction sites
2003 – 2004	staff member at the aerial archive of the department of prehistory and historical archaeology

2004 – 2015	associated member of VIAS, head of the group for Material Analysis, SEM and Theory of Science
2004 – 2006	staff member at archive of aerial archaeology of the University of Vienna
2005 – 2010	staff member at various archaeological surveys using 3d-Laserscanning
2005	Internship at Römisch Germanisches Zentralmuseum Mainz (RGZM), establishing a calibration curve for Micro-XRF.
2006 – 2010	Editorial department and distribution of VIAVIAS (Editor)
Since 2010	Employed by the LBI ArchPro (researcher)

Teaching at the Institute of Pre- and Early History / University of Vienna

Since 2000	Experimental Archaeology, workshop and lectures
Since 2005	Theory of Science, seminars and lectures

Related Activities and Experience

Since 2004	Atmospheric Secondary Electron Microscopy; International and interdisciplinary projects (Paleopathology, Anthropology, Archaeozoology, material analysis)
2004 – 2010	Presentation of the results of interdisciplinary research, philosophy of science and theoretical archaeology at various meetings
2006 – 2008	Staff member at the excavation in Schwarzenbach / Burg; Developement and testing of 3d digital documentation using 3d-Laserscanning
2007 – 2008	staff member at the LEOPOLD–project; 3d-data capturing and visualisation of archaeological contents
2007 – 2008	Management and documentation at the Researchers´Night 2007, Celtic Night;
	VIAVIAS 1 (Journal/Editor)
2008 – 2009	Preparation of projects, Evaluation of LEOPOLD, VIAVIAS 2 and 3, Cooperation with Centro Malqui/Peru and University of Sao Paulo/Brasil
Since 2010	Large Scale geophysical prospection and archaeological interpretation (LBI ArchPro)
Since 2011	case study leader of CS Kreuttal of the LBI ArchPro

2011/2012 technical director of the excavations at Ochsenberg/ Austria

Since 2012 General organisation of the case studies of LBI ArchPro, maintenance and logistics

2013 - 2014 3D laser scanning and Kite aerial photography at Akrotiri/ Greece

2013 – 2015 technical director of the excavations in Hornsburg/Austria

Since 2014 Virtual Archaeology (LBI ArchPro)

2015 – 2017 Project “A puzzle in 4D”, collaboration with OREA/ Academy of Sciences (LBI ArchPro)

Publications

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