THE COMPLEMENTARY USE OF NEUTRONS AND X-RAYS FOR THE NON-DESTRUCTIVE INVESTIGATION OF ARCHAEOLOGICAL OBJECTS FROM SWISS COLLECTIONS*

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This paper shows the possibilities offered by the combined use of non-destructive neutron and X-ray beams in archaeological research on metallic finds. The following five artefacts from Swiss excavations were submitted to investigation, each with dedicated aims: a Roman sword, a Roman dagger, an Iron Age bucket, Iron Age spearheads and a Roman finger ring. The images obtained with both methods—neutrons and X-rays—are discussed in length in this paper. The investigations took place at the Paul Scherrer Institute and the archaeologists who studied the objects come from the Universities of Lausanne and Zurich.

KEYWORDS: SWITZERLAND, LATE IRON AGE, ROMAN EMPIRE, NEUTRON-RAY, X-RAY, METALLIC FINDS

INTRODUCTION

Archaeological excavations in Switzerland have produced a very large number of finds from several different periods, including the Iron Age and the Roman era. Several important Roman settlements have been investigated and documented; for example, Vindonissa near Brugg, Augst near Basel and Avenches near Fribourg.

Hidden in the ground for almost 2000 years or longer, objects of archaeological importance and relevance have been damaged by their environment. When excavated, the corrosive and damaging process continues, and all investigations of the objects have to be performed very carefully to avoid damaging the objects further. Archaeologists ask different questions about their objects and answering them is often difficult due to the poor state of the objects. Scientific specialists have to obtain as much information as possible from the objects; modern methods from material science make this possible.

This paper uses several examples to demonstrate how a complementary application of neutron and X-ray transmission imaging has been used for the study of Iron Age and Roman objects found in different parts of Switzerland.

THE INTERACTION OF NEUTRONS AND X-RAY WITH MATTER

Both neutrons and X-rays have the ability to penetrate matter of a certain thickness. The attenuation of such beams depends on the material. Therefore, the measured transmitted signal of
the beam can be used as information about the often hidden material composition of the observed object.

The specific properties of either thermal neutrons or X-rays can be derived from Figure 1, where the attenuation coefficients are plotted versus the atomic number of the elements of matter. It is obvious that the attenuation of X-rays increases with higher mass numbers. Therefore, no transmission is possible for heavy elements and low sensitivity occurs for very light elements.

For neutrons, there is no general tendency visible for the attenuation coefficients. Contrary to X-rays, light elements such as hydrogen or lithium give high contrasts, whereas heavy elements such as lead, uranium or bismuth can easily be penetrated by thermal neutrons.

The reason for the differing behaviour of the two types of radiation has to do with the kind of interaction: neutrons only interact with the nuclei of atoms, whereas X-rays interact so with the electrons in the shell around the nuclei. With an increasing number of electrons, there is a higher probability of interaction (absorption, scattering).

Investigations using both methods are complementary, as alternative information is provided by the resulting images from the investigations due to the way in which neutrons and X-rays behave in their interaction with water. For the correct interpretation of these images, there must be a basic knowledge of beam transmission and attenuation. This is given in numerical form by the attenuation coefficients (see, e.g., Berger and Hubbell 1993–4; National Institute of Standards and Technology n.d.).

THE SET-UP OF TRANSMISSION RADIOGRAPHY SYSTEMS

X-ray imaging has been a conventional technique since the first observations of C. Roentgen in 1897. It is routinely used in medicine for diagnostic purposes, because the outer structures of the human body (flesh, fat and skin) can be penetrated, but bones or teeth give higher contrast and can therefore be inspected.
Non-destructive material testing of technical objects is also possible with X-rays, but a higher energy of radiation is required (up to 450 keV). Gamma sources such as Co-60 are used to penetrate much thicker material layers (initial energy about 1.2 MeV).

Regarding the investigation of metallic archaeological objects, the sensitivity to metals is of high importance. Outer structures of excavated objects (sands, soil, corrosive agglomerations and so on) can often be easily penetrated and the metal becomes visible.

Neutrons in use for radiography beam lines are either thermal or cold. Their properties with respect to material investigations are different and often complementary to X-rays. There is no real possibility of varying the neutron spectrum, because it is given by the neutron source (either a fission reactor or a spallation source). The typical energy for thermal neutrons is 25 meV, while for cold neutrons it is about 3 meV. However, the interaction probability can differ by up to a factor of three within this range, with the consequence of much higher contrast when cold neutrons are applied. The current investigations were carried out at a thermal beam line.

As shown in Figure 2, the set-up for transmission radiography starts from the source and goes via a beam-defining collimator through the object to the detector, which is considered as a two-dimensional array of point sensors for radiation. The pixel matrix then formats the transmission image (something like the shadow of the object with respect to the applied radiation).

The spatial resolution of state-of-the-art detectors is intrinsically in the order of 0.5–0.05 mm, depending on the set-up used and the detector parameters. Further limitations are imposed by the beam properties, by the interactions in the objects and by the electronic components.

When the objects have to be studied not just in one perspective but in three dimensions, the tomography run (Vontobel et al. 2003) requires sample projections from many rotational angles around the vertical axis. From this data, the full-volume information can be derived with the help of reconstruction tools (see, e.g., Kak and Slaney 2001). However, it is difficult to achieve the same spatial resolution as in the transmission images, not only because of the detectors used but also because of the huge amount of data for one object.

THE INVESTIGATIONS AT PSI

At the Paul Scherrer Institute (PSI) in Villigen (Switzerland), the neutron source used is based on the spallation process caused by protons in a heavy metal target (Bauer 1999). One of the beam lines with thermal neutrons is used for radiography and tomography purposes. This facility is called NEUTRA (Lehmann et al. 1996) and has excellent conditions for many practical and scientific applications using thermal neutrons with a beam diameter of up to 40 cm.
More extended objects can be scanned across this beam and the obtained images can be fitted together to form larger ones by image processing tools. This approach will be discussed later using examples. The facility is shown as a sketch in Figure 3 and as a real installation in Figure 4.

Unlike old traditions in radiography, where a film was the major or only radiation detector, so-called imaging plates (Takahasi et al. 1996) are applied for the transmission measurements. The transmission image data is directly available in digital format and the exposure time is 100 times less compared with film. This is especially relevant for neutrons where the risk of sample activation cannot be completely excluded when the beam is applied over minutes or hours. Another detection system is used for tomography, based on the light emission from a neutron-sensitive scintillator observed with a highly sensitive cooled CCD camera (Pleinert et al. 1997). X-ray inspection has been carried out at PSI’s School for Radiation Protection (see Paul Scherrer Institute n.d.), using a facility with an energy range between 40 kV and 125 kV of high voltage. The transmitted radiation is also detected using imaging plates, which are either the same as for neutron imaging or are purely gamma-sensitive ones. The exposure time was optimized according to the sensitivity of the detection system, which was tested with a special run in advance of the inspection of the archaeological objects.

As the same experimental technique was applied for both series of investigations, a direct comparison with the same spatial resolution was possible.

RESULTS OF NON-DESTRUCTIVE INVESTIGATIONS

This paper describes results from five series of investigations, which are typical with respect to the observed objects and can be taken as examples of what can be derived from complementary neutron and X-ray inspection. The continuation of this kind of study is foreseen in the near future.

A Roman gladius from the Legionary Camp of Vindonissa

Dimensions: total blade length 698 mm, length without hinge about 535 mm, width 70 mm; scabbard length 558 mm, maximal width 78 mm. Weight: 1148 g.
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This gladius of Mainz type (Fig. 5) was found in 1990 during excavations in the north of the legionary camp. It was lying in a pit within the ordinary soldiers’ quarters of a barrack block of the 21st Legion (AD 45–69), which was filled up at the earliest during the period of the 11th Legion (AD 70–101). In all likelihood, the sword and belt were made in workshops within the camp. On the basis of the images on the relief decoration and of the gladius form (Mainz type), it probably dates from the reign of Tiberius. Since the ensemble was deposited at the earliest around AD 50, and more likely in the later decades of the first century AD, the ‘life’ of the sword and belt can be determined as at least 30, or more probably 40–50, years (Deschler-Erb 1997, 2000; see also Peege 2002).

When the gladius was found, it was still in its scabbard, with belt pieces slung round the upper part of the weapon. The scabbard is constructed of several layers: the actual casing comprises the front and back of a board of lime wood. Over this, on the front, is a fairly large metal sheet, which is partly silver-plated and decorated with relief, and a smaller tongue of metal sheet, which is also decorated with relief. These pieces were held together by iron rims and a knobbed chape terminal. Over the basic construction are three scabbard clamps and a
Figure 5  The gladius of Mainz type from the legionary camp of Windisch-Vindonissa (Aargau, Switzerland). From top to bottom: drawings (Kantonsarchäologie Aargau), photographs of the front and back, a neutron-ray image (PSI) and an X-ray image (PSI).
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mouth-plate, the latter also decorated with relief. The reliefs along the length of the scabbard from top to bottom show a chained barbarian between two trophies, oakleaf wreaths, a thunderbolt with Jupiter’s hand, mounted combat, another trophy and a helmet.

Since a lot of competent conservation work has been carried out, the structure is clearly visible from the outside and parts of the bronze sealing can still be seen. The aim of the radiation transmission study with neutrons and X-rays was to find out more details about the hidden inner structure of the object. Of special interest was the question about the damage status at the time it was lost or hidden in the place of its later excavation.

The results of the investigations are shown in the lower images of Figure 5, where the metallic part that connects to the hilt is only shown in the neutron radiography. Although at first both images seem to be very similar, major differences can be identified in the fine detail.

Because X-rays are sensitive to metals but not to organic matter, the gladius itself is visible in the centre of the lower image inside the scabbard. Furthermore, the plating and the metallic connection of the two parts of the scabbard are clearly visible in the X-ray image (Fig. 5, X-ray). The scabbard clamps (formerly for connection to leather bands) seem to be of a different metal (brass or bronze), with a relatively higher X-ray attenuation than the steel of the sword. As a result, the X-ray image demonstrates that the metallic structure of the gladius is heavily damaged inside the scabbard, which is not indicated from the outside of the object.

The neutron image gives more detailed information about the scabbard itself, because the longitudinal stripes are related to wooden structures. This material becomes more visible with neutrons and the metal of the gladius is more transparent here than in the X-ray image. Furthermore, the conservation work with stabilizing resin, oil or adhesives can easily be inspected in the neutron image. Due to the high hydrogen content of these materials, cloudy and bubble-like structures become visible. As a consequence, in the future, neutron images of objects should be made before heavy applications of preservative agents.

A Roman dagger from Basel-Münsterhügel

Dimensions: total blade length 365 mm, blade length 252 mm, blade width 67 mm, hand hold length 113 mm, width at knob 42 mm, width at middle node 31 mm. Weight: 311.5 g.

The dagger was found in Basel Cathedral (excavation 1974/29), at the bottom of a cavity dating from the Tiberian era (about AD 15–30) and filled during the early period of Claudius (about AD 35–40). The cavity was carefully timbered and filled up all at once with material of mainly organic origin. Beside the dagger, an almost completely conserved ceramic container was also found. The placement of the dagger and the container might be seen as a ritual process (Furger n.d.).

The dagger is completely conserved, with its hilt and blade (Fig. 6, photograph). According to its wide blade and the withdrawn parts of the edge, the dagger corresponds to the Dunavöldvár type (Thomas 1971) or Type A (Scott 1985). Daggers of this type are dated between the reigns of Augustus and Claudius.

There are still unanswered questions since the discovery of the dagger (Furger n.d.): How was the blade built? Do the visible residuals of corroded parts on the blade (Fig. 6, photograph and drawing) belong to parts of the scabbard or to organic material of a cover (textile)? How was the hilt built?

In order to answer these questions, the dagger was investigated in May 2003 at PSI. Both X-rays and neutrons were applied. The most important results were obtained when both methods were compared simultaneously with the real object.
The Roman dagger from Basel-Münsterhügel (BS, Switzerland).

From left to right: a photograph, a drawing (Archäologische Bodenforschung Basel-Stadt), a neutron-ray image (PSI) and an X-ray image (PSI) of the front; and a photograph, a drawing (Archäologische Bodenforschung Basel-Stadt), a neutron-ray image (PSI) and an X-ray image of the side (PSI).
The blade structure  A central gutter with a sharp rib in the middle is clearly visible. Only the rib is visible from the outside (Fig. 6, photograph). The gutter and rib are characteristic of daggers of this type (Ypey 1961, 357; Thomas 1971, 47; Junkelmann 1986, 192). These features appear in the late Augustan period (Scott 1985, 165). The X-ray image helps to identify the forged structure of the blade. Some longitudinal tapes become visible along the middle axis. This might be an indication that the blade was damascened. It is also of importance that the dagger blade is well conserved, even if it does not appear so from the outside.

The scabbard  This can best be characterized by optical inspection in comparison with the neutron images. A cloudy layer, which does not cover all parts completely, lies above the blade (the dark spot at the end of the blade is an uncorroded stone). This thin covering layer is located close to the blade and cannot be a residual part of the scabbard. Commonly, scabbards are made of iron plates with a wooden insert (Junkelmann 1986, 192; Klein 2003, 57), and normally the scabbard should fit directly on to the parry bar. The structure visible on the neutron image suggests more a textile-like cover around the blade. This assumption is verified when the object is studied with the naked eye, focusing on the outer cover. Folding structures are visible, especially in the central region of the blade (Fig. 6, photograph and drawing), which could be explained as residuals of a textile (wool, leather). The dagger was certainly enveloped without its scabbard by a textile and placed into the cavity as mentioned above.

The construction of the hilt  In principle, the complicated layout of dagger hilts from early Roman Imperial times is well known. However, the analysis used for the investigation of the inner structure of the hilt allowed us for the first time to observe the construction without damaging the object in any way. From the inside towards the outside, there is first the hilt bar (Fig. 6, X-ray). It is probably a little thicker around the middle nod and has three rivet holes (Fig. 6, X-ray and neutron-ray images). The two rivet heads at the end of the hilt (visible from the outside) do not go through the hilt bar and must be considered as decorative elements. The dimensions of the rivet holes indicate that the hilt bar has a flat profile. Such cross-sections are considered an early chronological characteristic and cannot be dated later than the reign of Tiberius (Scott 1985, 162–3). The fixing rivet itself is only visible as a dark spot (Fig. 6, neutron-ray image). However, the neutron image and visual observation clearly show that the rivet is not missing. It is therefore thought that this fixing rivet was made of a non-ferrous metal alloy instead of iron. On the hilt bar some filling elements of bone sticks are assembled, which are very clearly visible in the neutron-ray image. In the middle of the hilt it appears that there is a combination of some sticks and pieces of the same material. On the basis of the neutron image, it is not possible to decide whether the filling material is wood or bone. However, a material determination was made by minimal invasive optical inspection into the middle nod of the hilt. With the microscope at the position where the filling parts are open, bone structures were identified by S. Deschler-Erb (Institut für Prähistorische und Naturwissenschaftliche Archäologie/IPNA, Basel).

The whole hilt is covered on both sides by iron cladding, made in two halves. This cladding is clearly visible on the X-ray image and by outer optical inspection. Besides the adornment rivets mentioned above, no special features can be found on the two sections of cladding. They are connected together with three fixing rivets. The hilt is followed directly by the parry bars, which sit on the top of the blade. In principle, they are made in the same fashion as the hilt and again covered with iron cladding, formed in two halves (Fig. 6). The neutron image shows that bone sticks are used as filling elements, placed on the iron core. The two central ones are clearly visible as dark points, which are connected via holes through the blade. Bored shoulders
of dagger blades can be found in most cases on daggers attributed to the era of Augustus and Tiberius (Scott 1985, 163). The two outer fixing rivets are only visible in the neutron images and by the naked eye. They are used exclusively to fix the ends of the parry bars.

The analysis of the early Roman Empire dagger from Basel provides a good example of how the different non-destructive methods can be used for a combined investigation.

An Iron Age bucket from Giubiasco, reconstructed into a helmet

Dimensions: length 300 mm, width 230 mm, height 250 mm.

In 1901, about 480 graves were found in the graveyard of Giubiasco (TI), 50 of which contained weapons. The graves with weapons range from the late Iron Age to the beginning of the Roman period (Pernet et al. 2002). The archaeological materials from these graves are now stored at the Swiss National Museum (Zurich), and the story of the excavations is being reassessed (Tori et al. 2004). In grave 330, an artefact interpreted as a helmet was found. It is made of bronze sheets and wood, and was greatly restored at the beginning of the 20th century in order to resemble a helmet. However, a recent article published on the subject has shown that it could in fact be a late Iron Age bucket, made of bronze and wood (Pernet 2002). The bronze elements were the only original parts kept for restoration. Part of the original wood had been found, but was not included in the restoration. The bronze hoopings were mounted on to a new body made of wood and leather, giving the object a peculiar aspect, which is unknown in Iron Age helmets (Fig. 7, photographs).

In order to better understand how the object was restored and what its function really was, the PSI performed a series of neutron rays, X-rays and a neutron-ray tomography of the artefact. The main aim was to separate the original materials from those used in the restoration.

A comparison of the neutron-ray and X-ray images allows the following comments to be made. First, because the organic materials (leather and wood) used for the restoration are not as deteriorated as they are on the previous examples from Vindonissa and Basel, their strong interaction with the neutrons hides the metallic parts. In this case, the neutron-ray image cannot show both the organic and the metal materials together. Moreover, the thickness of the wood makes it difficult to interpret the view (Fig. 7, neutron-ray image). The same problem occurred with the neutron-ray tomography, and it has not been possible to separate, on the images, the bronze hoopings from the wooden body. Therefore, a 3D reconstruction of the object based on the tomography carried out using the original parts is impossible. It is in fact the X-ray image that provides new information. Not only is the bronze clearly visible, but a number of hidden nails, used by the restorers to hold the bronze on to the wood, can also be seen (Fig. 7, X-ray).

In this analysis, the use of X-rays has given more information than the neutron rays, and it confirms that this object that has the actual shape of a helmet is probably a bucket or a vessel of some sort, made of bronze and wood.

Iron Age spearheads from Giubiasco

Dimensions of spearhead from grave 125: length 210 mm, width 36 mm.

Corroded spearheads from the graves of Giubiasco were submitted to the PSI for further analysis. They are made entirely of iron, apart from mineralized wood that remains in some of the sockets (Fig. 8, drawing). There were several aims: to compare the images made using
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X-rays and those made using neutron rays, and also to obtain sections of the spearheads using neutron-ray tomography.

The spearhead from grave 125 is used as an example. A comparison of the neutron-ray images with the more traditional X-rays allows the following observations to be made (Fig. 8, neutron-ray and X-ray images). The low interaction of neutrons with iron gives 2D images of the spearheads that flatten the blades and give no idea of their volume. On the other hand, the X-ray images show that the centre of the blade is thicker than the sides and still contains some iron. The sockets are also seen better on the X-ray images. As the spearheads were restored at the beginning of the 20th century with organic products (linseed oil, Vaseline, etc.), these products interact with the neutrons and appear in the sockets. They do not appear on the X-ray images. In the case of a pure iron object, using both X-rays and neutron rays, it is on the X-ray images that the information most useful for the archaeologist can be found (construction of the object, thickness of the metal, etc.).

Besides the 2D images, the neutron-ray tomography of one spearhead has been performed at the PSI (Fig. 8, neutron-ray tomography). The purpose was to obtain sections of the object without having to proceed to any intrusive restoration (chemical bath, mechanical removal of the corrosion, etc.). The tomography images gave good results. Without any cleaning, it was possible to establish that under the corrosion, the section of this spearhead is lenticular (no central rib; see Fig. 9); this confirms the first impression given by the 2D X-ray images. Such observations can be very useful on large series of objects, where sections are needed in order to make typologies based on the morphology of the objects.
Figure 8. The spearhead from Giubiasco grave 125 (Ticino, Switzerland). From left to right: a drawing (I. Frei, Swiss National Museum, Zurich); a neutron-ray image (PSI); a neutron-ray image from a tomography run, central slice (PSI); and an X-ray image (PSI).

Figure 9. The spearhead from Giubiasco grave 125 (Ticino, Switzerland). Sections from neutron-ray tomography run (PSI). Upper: the blade of the spearhead from top to bottom. Lower: the socket of the spearhead from top to bottom.
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A Roman finger ring from Giubiasco

Dimensions: diameter about 25 mm.

A Roman finger ring found in a grave at Giubiasco was also submitted for X-rays, neutron rays and neutron-ray tomography at the PSI. The first aim was determine whether the intaglio (engraved stone) was still in place under the corrosion or whether it was gone. Again, the idea was to answer this question without any restoration. The neutron-ray and X-ray images clearly show that there is an empty hole where the intaglio had been placed earlier (Fig. 10). Following that, a neutron-ray tomography of the ring was performed in order to investigate the precision with which images of such a small object could be obtained. The result is very accurate and the images extracted from the tomography give a very detailed view of the empty hole (Fig. 11).

CONCLUSIONS

The analyses described in this paper show how valuable the complementary use of X-ray and neutron-ray images is, and in which cases this combination of techniques gives the best results. The use of neutron rays combined with X-rays is very rewarding if mineralized organic elements (wood, bone, wool, etc.) are stuck to the metallic parts of an object. Often, archaeologists only proceed to X-ray analysis (the neutron ray is still expensive), but the example of the Roman dagger from Basel-Münsterhügel (BS), wrapped in textile, shows very clearly how much extra information can be obtained from an neutron-ray image in addition to an X-ray and inspection of the object itself. The Paul Scherrer Institute (PSI) in Villigen provides such opportunities.
However, neutron-ray images do not always provide the information that is expected. Two cases from Giubiasco (TI)—a pure iron object (a spearhead) and an object that has recently been restored using organic materials (essentially, wood)—show this well. Here, it is mainly on the X-ray images that the expected information is found. The use of these different beams is therefore closely linked to the type of object submitted for analysis and the information expected by the archaeologist.

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