



HAL
open science

NEW INSIGHTS INTO THE DATING OF ROMAN AND MEDIEVAL MORTARS BY OPTICALLY STIMULATED LUMINESCENCE [OSL]: COMPARISON OF CASE STUDIES

Petra Urbanová, Pierre Guibert

► To cite this version:

Petra Urbanová, Pierre Guibert. NEW INSIGHTS INTO THE DATING OF ROMAN AND MEDIEVAL MORTARS BY OPTICALLY STIMULATED LUMINESCENCE [OSL]: COMPARISON OF CASE STUDIES. Brian Bowen; Donald Friedman; Thomas Leslie; John Ochsendorf. Proceedings of the Fifth International Congress on Construction History Chicago June 2015, 3, pp.499-508, 2015, 978-1-329-15035-5. <hal-02535216>

HAL Id: hal-02535216

<https://hal.science/hal-02535216v1>

Submitted on 7 Apr 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

NEW INSIGHTS INTO THE DATING OF ROMAN AND MEDIEVAL MORTARS BY OPTICALLY STIMULATED LUMINESCENCE [OSL]: COMPARISON OF CASE STUDIES

Petra Urbanova¹, Pierre Guibert²

Keywords

Mortar, Dating, Construction, Middle-Ages, Roman Antiquity, Optically Stimulated Luminescence

Abstract

Mortar is the material common to a majority of historical buildings which because of its mechanical properties cannot be replaced without being destroyed. Its making is undoubtedly contemporary to the building. That is the reason why the dating of mortar is a very convenient element for understanding the history of construction.

In theory, lime mortars composed of a mixture of lime and sand may be dated by optically stimulated luminescence [OSL]. The basic premise in such an analysis is that quartz in the sand used for making mortar is optically zeroed during the process of quarrying and mixing. Several seconds of exposition to daylight are enough to set the “chronometer” to zero. Mortar is then embedded within the masonry to bind building elements, and thus it is hidden from light. The moment to be dated is this last exposition to photons. To get over the heterogeneity of the material studied, quartz grains from mortar are analysed individually using a “single grain technique”.

This paper explains the basics of the OSL dating method and presents it in the context of this exploratory application. The OSL ages obtained for the series of reference mortar samples are compared with known independent ages based on archaeomagnetic dating and archaeological conclusions. The aim is to confirm the validity of the method.

The mortar samples studied originate from diverse geological areas and thus vary in mineral composition from one to another. The characterization of their microstructure is one of the important stages indicating the OSL dating potential and alternatively allowing us to distinguish between different construction phases. We propose a deeper insight into this promising technique by demonstrating the results of our research on reference mortar samples originating from three Roman sites in France [the Palais-Gallien amphitheatre in Bordeaux, the Longeas thermal baths in Chassenon and the Roman foundations of the medieval Château Grimaldi in Antibes].

¹ IRAMAT-CRP2A, Institut de Recherche sur les ArchéoMATériaux - Centre de Recherche en Physique Appliquée à l'Archéologie, UMR5060 CNRS-Université de Bordeaux Montaigne, Maison de l'Archéologie, Esplanade des Antilles, 33607 Pessac, France, Petra.Urbanova@u-bordeaux-montaigne.fr

² IRAMAT-CRP2A, Institut de Recherche sur les ArchéoMATériaux - Centre de Recherche en Physique Appliquée à l'Archéologie, UMR5060 CNRS-Université de Bordeaux Montaigne, Maison de l'Archéologie, Esplanade des Antilles, 33607 Pessac, France, Pierre.Guibert@u-bordeaux-montaigne.fr

INTRODUCTION

These days the importance of archaeometry and its interdisciplinary connection to archaeology and the natural sciences is still on the rise. In the field of construction history where the questions of chronology are an omnipresent topic, absolute dating methods, especially when combined with archaeological and historical sources of knowledge, can often bring original information and contribute significantly to the better understanding of history of building. In this paper, we focus on luminescence dating, the method whose basics were established and understood during the 60's and which had been fully developed and tested on diverse archaeological material such as ceramics and fired bricks in the laboratories of Oxford and Denmark [Risø] by the end of the 70's (Aitken et al. 1964; Mejdahl 1969; Zimmerman 1971). The wider use of this method in building archaeology appeared later with the increasing interest in the thermoluminescence dating of architectural ceramics (Goedicke et al. 1981; Guibert et al. 1998; Bailiff et Holland 2000). In many situations thermoluminescence [TL] and optically stimulated luminescence [OSL] of fired bricks were employed as complementary methods to radiocarbon dating in the absence of an organic element in a dated structure assuming the contemporaneity of the brick production and the construction of the given building. Many recent studies underline the importance of the complementarity of various dating methods such as dendrochronology, radiocarbon, luminescence and archaeomagnetism (Gallo et al. 1999; Blain et al. 2007; Guibert et al. 2009; Blain et al. 2011). The study of the interdisciplinary European research group "Ceramic Building Materials and New Dating Methods" whose results were presented at the last International Congress on Construction History in Paris in 2012 (Guibert et al. 2012) revealed an important number of case studies proving the frequent re-use of bricks originating from older structures in the Middle-Ages. In consequence, dating of bricks is not always indicative when dating the erection of the masonry. That is why our attention is now being turned towards mortar, the material common to a majority of historical buildings since it cannot be replaced without being destroyed, because of its mechanical properties. Its making is undoubtedly contemporary to the building.

The unique advantage of mortar dating for building archaeology by radiocarbon was recognized in the 60's (Labeyrie 1964). Since the 80's attempts have been focused not only on the dating of organic remains (charcoals) in mortar, but also on analyses of calcite formed through the carbonation process (Pesce and Ball 2012) in some cases. However, due to various difficulties the radiocarbon method cannot be universally used. Thus, optically stimulated luminescence [OSL] becomes a promising alternative.

A few isolated solitary experiments in mortar dating by OSL were performed between 2000 and 2013 (Bøtter-Jensen et al. 2000a; Goedicke 2002; Zacharias et al. 2002; Jain et al. 2004; Goedicke 2011; Gueli et al. 2010; Panzeri 2013). All these publications indicate the potentialities of dating mortars by OSL, however, what is lacking is a deep methodological study systematically testing a larger spectrum of mortar samples from different areas. The objective of the ongoing exploratory research is to test the applicability of OSL on archaeological mortars by dating the quartz grains of different mortar samples originating from reference structures that are already correctly dated by other physical and historical approaches and thereby to establish a suitable methodology.

ARCHAEOLOGICAL CONTEXT AND SAMPLING

Studied Monuments

In this paper we present OSL dating applied on mortar samples originating from three Gallo-Roman archaeological monuments (Table 1). The medieval Grimaldi castle in Antibes located on the French Riviera is constructed on the ancient *acropolis* called Antipolis. The foundations of the castle, built with stones and bricks and rising over several meters in height, represent part of an unknown Roman building which was sampled for dating purposes. The Roman baths of Chassenon, historically called Thermes de Longeas in Cassinomagus village, are situated in Charente department in central western of France. Mortar for OSL dating was sampled in the foundations of the baths in one of the underground caves. The ruins of the Palais-Gallien Roman amphitheatre in Bordeaux lie in the Aquitaine region in south-western France and represent the only visible Roman structure of the ancient Roman city of Burdigala. Mortars from foundations and from between brick layers were sampled in the standing part of the ruins. All mortar samples were taken using a core drill of 50 mm in diameter designed for wet cutting.

BASICS OF LUMINESCENCE DATING

Physical Principle Of The Method

The method of optically stimulated luminescence, based on the existence of natural radioactivity, studies the dosimetric properties of minerals present in sediments and materials originating from anthropic activity, such as bricks or mortar. Natural radioactive elements, potassium, uranium and thorium, present in the studied material are submitted to spontaneous disintegration resulting in the emission of ionizing radiation. In consequence, the surrounding irradiated minerals such as quartz [present in mortar] store this energy which provokes the detachment of electrons from their parent nuclei and their being trapped at some defect in the lattice that is attractive to electrons [e.g. oxygen vacancies or substitution impurity atoms]. As a result of this exposure to ionizing radiation mineral grains used for dating acquire a population of trapped electrons. The number of electrons trapped increases with the age of the sample. The more prolonged the exposure to nuclear radiation the greater the number of trapped electrons. In other terms, the older the material the larger the amount of energy accumulated. When the material is exposed to light of a particular stimulation wavelength, captured electrons are evicted from the trap. If the detrapped electron then recombines in a “luminescence center”, the energy released during this process gives rise to the emission of light and this emitted luminescence is what we measure in the laboratory for dating purposes. The exposure to light thereby provokes optical zeroing [bleaching] of the material. Afterwards, when the material is hidden from light, the process of electron trapping starts again and continues until the next zeroing event.

The key elements used for the OSL dating of mortar are the quartz grains contained in the sand. In theory, the sequence of events leading to the preparation of mortar, from extraction of sand in a quarry and its transport to a building yard to mixing with lime binder, allows the bleaching and resetting of the quartz minerals. Once prepared, the mortar is embedded within a built structure, thus hidden from light and the process of electron transfer starts and continues until the moment of dating. The measurement of the luminescence, of the amount of energy accumulated since this last exposure of mortar to light is crucial for dating the erection of a given building.

To get the age of a sample, two parameters have to be determined. Luminescence, a total amount of energy accumulated since the last exposure of mortar to light called “archaeological

dose” or “paleodose” has to be divided by the amount of energy accumulated every year called “annual dose” according to the equation $T = Q/A$ where Q [expressed in grays: Gy] corresponds to the average archaeological dose, A [gray per year: Gy/y] to the value of the annual dose and A [year] to the age obtained. The dose absorbed per year is considered to be stable through time. Among many different factors whose contributions are added together, there are two that have particular importance for the evaluation of the annual dose: the radiation emitted from the dated object estimated by gamma spectrometry measurements and the contribution of the environment surrounding the sample determined by using *in situ* dosimetry. The procedure of annual dose determination is well-understood and follows a routine procedure. On the contrary, the evaluation of the archaeological dose remains a real challenge.

Single Grain Technique

For the presented samples the proportion of quartz grains that exhibit a measurable signal as a response to OSL stimulation does not exceed 8 %. Therefore, several thousand grains need to be measured in order to obtain a good statistical representativeness.

Bleaching of grains takes place during the extraction and transport of sand and the preparation process of mortar. The exposure of individual grains to light is not necessarily uniform. Depending on the preparation procedure and the quantity of prepared material some grains may happen to be insufficiently exposed to light. Therefore, they won't be completely reset to zero. As a result, these grains will contain a certain residual dose, so they will emit a higher signal than expected for dating and will thereby make the sample seem older. That is why the grains have to be analyzed separately one by one. After the analysis of approximately 4000 grains, 92 % of which do not give any signal, 8 % of grains are left. These grains are studied in detail in order to select those that were reset to zero at the moment of the construction and that contain the right chronological information, so they can thus be used for the calculation of the average archaeological dose.

RESULTS AND DISCUSSION

Distributions Of Individual Archaeological Doses

The histograms shown represent the measured distributions of archaeological doses for individual grains of three different mortars. For the Antibes samples (Figure 1a) significantly narrow distribution is observed indicating a good degree of bleaching of these mortars. A Chassenon sample (Figure 2a) reveals a somewhat larger distribution implying a presence of some scarce poorly bleached grains in mortar, which nevertheless at the same time, contains enough grains that give the right chronological information. Thus, for the Antibes and Chassenon samples average archaeological doses were calculated according to the “central age model” (Galbraith et al. 1999), a sort of a weighted mean usually employed for an OSL data evaluation in the case of well-bleached samples. The dates obtained are in good agreement with the time intervals determined by archeomagnetism and also with the archaeological conclusions (Table 1) which validates the reliability of the method.

The distributions of archaeological doses measured for the samples from Palais-Gallien [Bordeaux] are largely dispersed (Figure 3a). The lowest doses generally correspond to better bleached grains while the large proportion of high doses represents the rather poorly bleached grains. If all the grains were included in the calculation of the average archaeological dose, the result would be an over-estimation of the ages obtained. Different solutions to evaluate the obtained data are currently being analyzed and the results will be published in future months.

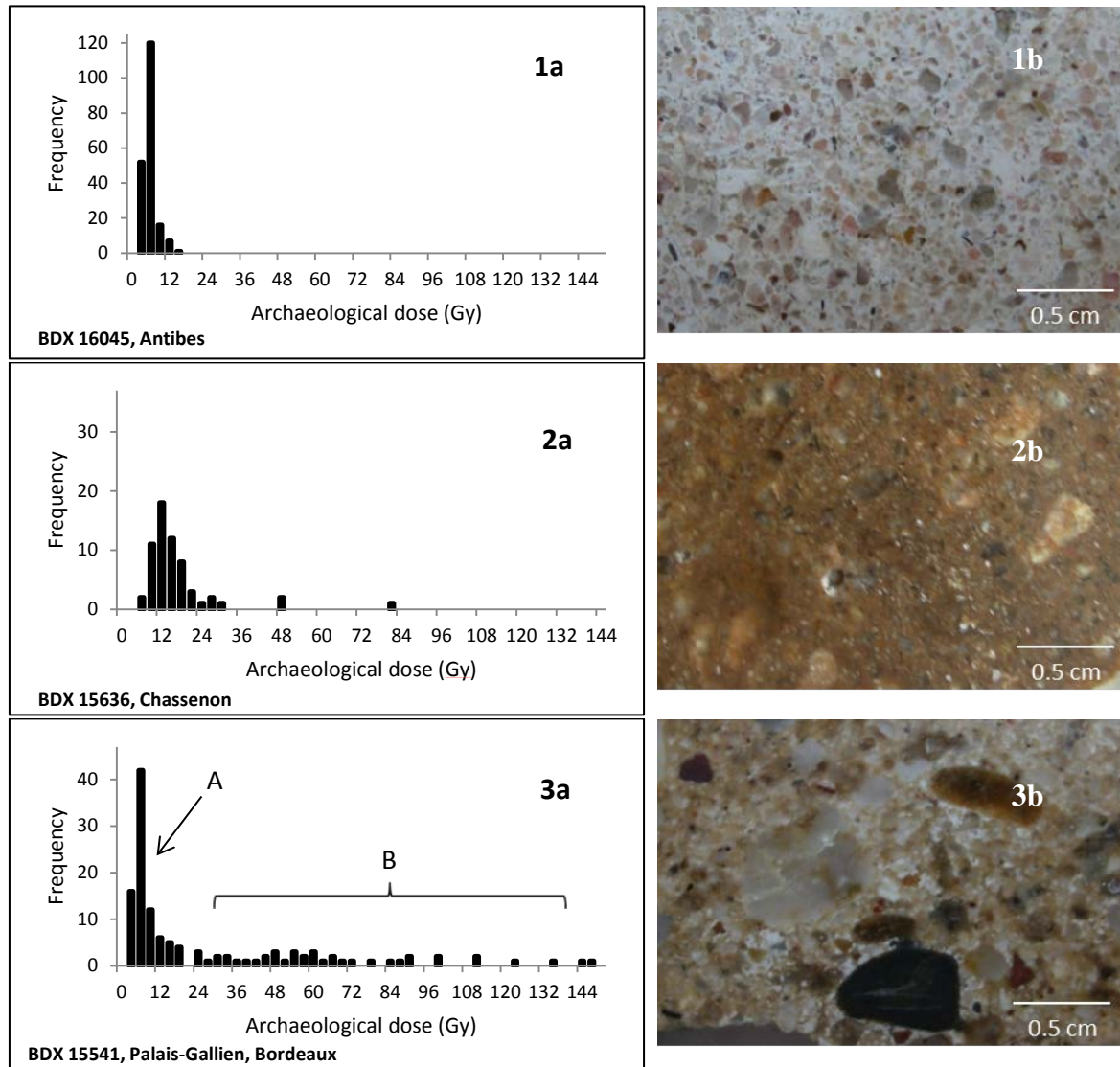


Figure 1-3: Graphical presentation of distributions of archaeological doses measured for individual quartz grains by the single grain technique and photographs of corresponding mortar samples [Antibes - 1a, 1b; Chassenon - 2a, 2b; Palais-Gallien, Bordeaux - 3a, 3b]

Sources Of Dispersion Of Individual Archaeological Doses

The crucial element is to understand the reasons why in the case of the samples from Palais-Gallien in Bordeaux such a pattern of distribution is obtained. The dispersion of individual archaeological doses is principally linked to insufficient bleaching (insufficient exposure to light) that shows in a higher dose region (Figure 3a, part B). Another phenomenon whose influence is visible mainly on a low dose part of the distribution (Figure 3a, part A) is heterogeneous microdosimetry caused by inhomogeneous distribution of irradiation sources in the material. To verify this hypothesis mapping by scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX) was performed in order to assess the spatial distribution of potassium, one of three principal radioelements causing the irradiation of surrounding minerals on a millimeter scale [similar to penetration power of beta particles]. Figure 4 shows that the distribution of potassium feldspars [minerals the richest in potassium present in mortar] is not homogeneous. Ap-

parently, the grain in zone 1 located between two large potassium feldspars is submitted to stronger irradiation than the grain in zone 2 located much further away and not having any such mineral in its nearest environment. Therefore, the first grain, being more irradiated, will exhibit a higher archaeological dose than the second one and it will thereby seem older. In this context, the analysis of the micro-texture and structure may be helpful in understanding the differences between samples of various origins.

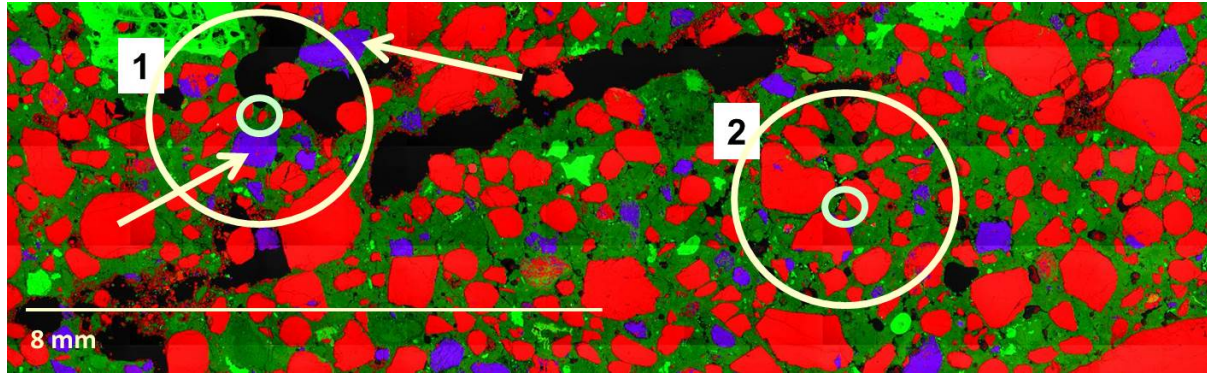


Figure 4: Colored interpretation of scanning electron microscopy mapping of the sample BDX 15541, Palais-Gallien, Boreaux: red - quartz minerals, blue - potassium minerals, green - calcium matrix.

Characterization Of Studied Mortars

The dated mortars were characterized by polarizing microscopy in thin section. The most striking feature that distinguishes Palais-Gallien mortars [Bordeaux] from the others is their coarse-grained character (Figure 3b). The Palais-Gallien samples contained a lot of potassium feldspars and, at the same time, plenty of quartz gravels measuring one or several centimeters in diameter. These observations confirm the heterogeneity of the studied material which will make the OSL dating procedure more complex. The minerals had a rounded shape indicating, from a geological point of view, a long natural transportation process of grains. Unlike the mortar from Palais-Gallien [Bordeaux] the Antibes samples represent small-grained and homogeneous material (Figure 1b) with mostly angular grains containing a lot of binder and rich in micas. The Chassenon mortar was also relatively small-grained (Figure 2b) compared to the Palais-Gallien samples [Bordeaux], containing angular grains of a local granitic origin and several large rock fragments. The samples were extremely rich in feldspars and contained low proportions of quartz. The quantity of material for OSL dating was therefore restricted.

Dating Results

Monument studied	Archaeological conclusion	Archeomagnetic dating result	OSL dating result
Grimaldi castle, Antibes	[before 50 AD]	[250 BC, 86 AD]	[8 BC, 224 AD]
Roman baths, Chassenon	[90 AD, 170 AD]	[84 AD, 443 AD]	[18 BC, 280 AD.]
Palais-Gallien, Bordeaux	[80 AD, 150 AD]	[65 AD, 171 AD]	-

Table 1: Interdisciplinary comparison of chronological results (Urbanova et al. 2015; Urbanova, in preparation). Archaeomagnetic results (Lanos ans Dufresne 2013) are presented with 95% level of confidence interval.

To conclude, the dating results of Antibes and Chassenon (Urbanova, in preparation) are in both cases in very good agreement with the results of archaeomagnetic dating (Lanos et al. 1999)

and with archaeological conclusions (Table 1). Because of the large dispersion of individual archaeological doses, the dates for the series of the Palais-Gallien samples [Bordeaux] could not have been calculated by the standard approach, however, the reasons that explain the observed dispersion of archaeological doses were well-understood (Urbanova et al. 2015).

CONCLUSION

Two out of three monuments tested, Antibes and Chassenon, could have been directly dated by OSL using the single grain technique with the complete concordance of OSL, archaeomagnetic and archaeological data. On the contrary, we did not succeed in finding a universal procedure to determine the age of the poorly bleached Palais-Gallien samples [Bordeaux] by standard OSL approaches, which implies the need to attempt another solution for the statistical treatment of the data that is adapted to the given series of samples and that would allow to extract the right chronological information from the measured OSL data. Especially in the case of such a series of samples, the indispensability of using the single grain technique is obvious. It allows to distinguish complex case studies and also to evaluate the reliability of the age obtained. If a distribution of measured archaeological doses is not dispersed, the samples are most likely to give correct results. In the opposite case the evaluation of experimental data must be carried out with precaution.

The properties and characteristics of mortar mainly depend on the nature of a binder and a filler component, their proportion and the way these materials were treated by ancient builders. Taking previous observations into account, small-grained and homogeneous mortar probably have better potential for easy dating by OSL. Knowledge of a microstructure and the preliminary characterization of studied mortar are thus indispensable in order to understand all the effects occurring in the material.

In this paper OSL dating was firstly applied to Roman structures, which are older and thus exhibit higher and more easily exploitable signal in comparison with medieval structures. At this moment, when the methodology of the procedure is established, the dating of two medieval monuments, the Saint Seurin basilica in Bordeaux and the Basler Münster cathedral is in progress. The results will be presented at the upcoming meeting.

The study shows promising potential for optically stimulated luminescence [OSL] to date archaeological mortars, which represents a step forward in the fields of archaeology and construction history in the cases where other methods have reached the limits. The next goal will be to employ OSL dating of mortar on unknown or insufficiently dated structures and to help in understanding more complex archaeological problems as well as unanswered historical questions.

ACKNOWLEDGEMENTS

We are grateful to the following organizations which have supported this research financially: CNRS-INSHS [French National Center for Scientific Research - Institute of Human and Social Sciences], Conseil Régional d'Aquitaine [equipment], University Bordeaux-Montaigne [PhD grant and special support for research programs], Mairie d'Antibes, Conseil Régional de la Charente, Mairie de Bordeaux. This project was co-financed by the labex LaScArBx [Bordeaux Archaeological Sciences Labex] administrated by ANR [Agence Nationale de la Recherche] with the reference ANR-10-LABX-52. We would also like to express our thanks to the following institutions for the authorization to sample the studied monuments: Mairie de Bordeaux, Service Régional de l'Archéologie d'Aquitaine, Service des Monuments Historiques, Conseil Général de la Charente, Mairie d'Antibes, Musée Picasso. Special thanks to Virginie Moineau [assistant

engineer], to Eric Delaval [archeologist, Ville d'Antibes], to David Hourcade [archaeologist, Communauté Urbaine de Bordeaux, associated researcher, UMR Ausonius], to Claude Ney [CNRS, IRAMAT], to Yannick Lefrais, engineer, for his helpful assistance in SEM-EDS mapping and finally to Guillaume Guérin for numerous valuable pieces of advice.

REFERENCES

- Aitken, M., Tite, M., Reid, J. 1964. "Thermoluminescence dating of ancient ceramics." *Nature*, 202 (1032-1033).
- Bailiff, I., Holland, N. 2000. "Dating bricks of the last two millennia from Newcastle upon Tyne: a preliminary study." *Radiation Measurements*, 32 (615-619).
- Blain, S., Guibert, P., Bouvier, A., Vieilleveigne, E., Bechtel, F., Sapin, C., Baylé, M. 2007. "TL-dating applied to building archaeology: The case of the medieval church Notre-Dame-Sous-Terre (Mont-Saint-Michel, France)." *Radiation Measurements*, 42 (1483-1491).
- Blain, S., Guibert, P., Prigent, D., Lanos, P., Oberlin, C., Sapin, C., Bouvier, A., Dufresne, P. 2011. "Dating methods combined to building archaeology: the contribution of thermoluminescence to the case of the bell tower of St Martin's church, Angers (France)." *Geochronometria*, 38:1 (55-63).
- Bøtter-Jensen, L., Solongo, S., Murray, A., Banerjee, D., Jungner, H. 2000a. "Using OSL single-aliquot regenerative-dose protocol with quartz extracted from building materials in retrospective dosimetry." *Radiation Measurements*, 32:5-6 (841-845).
- Galbraith, R., Roberts, R., Laslett, G., Yoshida, H., Olley, J. 1999. "Optical dating of single and multiple grains of quartz from Jinmium Rock Shelter, Northern Australia: part I, experimental design and statistical models." *Archaeometry*, 41:2 (339-364).
- Gallo, N., Fieni, L., Martini, M., Sibilina, E. 1999. "Building archaeology, 14C and thermoluminescence: two examples comparison." *Proceedings of « C14 et Archéologie » meeting*, Suppl. Revue d'Archéométrie 1999 and Mémoires Société Préhistorique Française XXVI (425-431).
- Goedicke, G. 2011. "Dating mortar by optically stimulated luminescence: a feasibility study." *Geochronometria*, 38:1 (42-49).
- Goedicke, G. 2002. "Dating historical calcite mortar by blue OSL: results from known age samples." *Radiation Measurements*, 37 (409-415).
- Goedicke, C., Slusallek, K., Kubelik, M. 1981. "Thermoluminescence dating in architectural history: Venetian villas." *Journal of the Society of architectural Historians*, XL:3 (203-217).
- Gueli, A., Stella, G., Troja, S., Burrafato, G., Fontana, D., Ristuccia, G., Zuccarello, A. 2010. "Historical buildings: Luminescence dating of fine grains from bricks and mortar." *Il Nuovo cemento*, 125 B.
- Guérin, G., Mercier, N., Adamiec, G. 2011. "Dose-rate conversion factors: update." *Ancient TL*, 29 (5-8).

- Guibert, P., Ney, C., Bechtel, F., Shvoerer, M., Araguas, P. 1998. "Datation par thermoluminescence d'éléments architecturaux en terre cuite de la Seo del Salvador, église cathédrale de Saragosse, Espagne." *Revue d'Archéométrie*, 22 (125-135).
- Guibert, P., Bailiff, I., Blain, S., Gueli, A., Martini, M., Sibilina, E., Stella, G., Troja, S. 2009. "Luminescence dating of architectural ceramics from an early medieval abbey: the St-Philbert intercomparison (Loire-Atlantique, France)." *Radiation Measurements*, 44:5-6 (488-493).
- Guibert, P., Bailiff, I., Baylé, M., Blain, S., Bouvier, A., Büttner, S., Chauvin, A., Dufresne, P., Gueli, A., Lanos, P., Martini, M., Prigent, D., Sapin, C., Sibilina, E., Stella, G., Troja, O. 2012. "The use of dating methods for the study of building materials and constructions: state of the art and current challenges." *Proceedings of the 4th International Congress on Construction History*, Paris 3-7 July 2012 (469-480).
- Jain, M., Thomsen, K., Bøtter-Jensen, L., Murray, A. 2004. "Thermal transfer and apparent-dose distributions in poorly bleached mortar samples: results from single grains and small aliquots of quartz." *Radiation Measurements*, 38 (101-109).
- Labeyrie, J., Delibrias, G. 1964. "Dating of old mortars by the carbon-14 method" *Nature*, 201 (742).
- Lanos, P., Dufresne, P. 2013. "Chassenon (Charente) Thermes de Cassinmagus, Cave 10. Analyse archéomagnétique." Rapport 2013.
- Lanos, P., Dufresne, P. 2013. "Antibes (Alpes-Maritimes), Château Grimaldi, Mur MR 10003. Analyse archéomagnétique." Rapport 2013.
- Lanos, P., Kovachva, M., Chavin, A. 1999. "Archaeomagnetism, methodology and applications: implementation and practice of the archaeomagnetic method in France and Bulgaria." *European Journal of Archaeology*, 2(3), 365-392.
- Mejdahl, V. 1969. "Thermoluminescence dating of ancient danish ceramics" *Archaeometry*, 11 (99-104).
- Panzeri, L. 2013. "Mortar and surface dating with optically stimulated luminescence (OSL): Innovative techniques for the age determination of buildings." *Nuovo Cimento della Società Italiana di Fisica C*, 36:4 (205-216).
- Pesce, G., Ball, R. 2012. "Dating of Old Lime Based Mixtures with the Pure Lime Lumps Technique." *Radiometric Dating*, Dr. Danuta Michalska Nawrocka (Ed.), ISBN: 978-953-51-0596-1, InTech.
- Urbanova, P., Hourcade, D., Ney, C., Guibert, P. 2015. "Sources of uncertainties in OSL dating of archaeological mortars: the case study of the Roman amphitheatre *Palais-Gallien* in Bordeaux." *Radiation Measurements*, 72 (100-110).
- Urbanova, P., Guibert P. in press. "Datation des mortiers de chaux par luminescence optique stimulée (OSL): une nouvelle approche de la chronologie de construction." *Proceedings of Deuxième Congrès Francophone d'Histoire de la Construction*, Lyon, January 29-31, 2014.

Urbanova, P., in preparation. Researches on direct dating of constructions: Investigations of the potential of optically stimulated luminescence to date archaeological mortars. PhD thesis, University Bordeaux Montaigne.

Zacharias, N., Mauz, B., Michael, C. 2002. "Luminescence quartz dating of lime mortars. A first research approach." *Radiation Protection Dosimetry*, 101 (379-382).

Zimmermann, D. 1971. "Thermoluminescence dating using fine grains from pottery." *Archaeometry*, 13 (29-52).