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Artificial Intelligence Applied to Byzantine Sigillography: Current Research, Challenges, and Future Perspectives

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Neural networks have grown to a crescendo, becoming a cornerstone of current artificial intelligence (AI) systems. They are used in diverse real-world applications in nearly every domain, including medicine, arts, humanities, and social sciences. However, only a few works have applied them to Byzantine sigillography. This paper addresses the specificities of Byzantine seal images and how neural network algorithms must be adapted to help with their analysis. We also discuss the challenges, opportunities, and potential of combining different artificial intelligence methods to analyze Byzantine seals.

Les réseaux neuronaux ont connu un essor considérable, devenant une composante essentielle des systèmes actuels d’intelligence artificielle (IA). Ils sont utilisés dans diverses applications concrètes dans presque tous les domaines, notamment la médecine, les arts, les sciences humaines et sociales. Cependant, seuls quelques travaux les ont appliqué à la sigillographie byzantine. Cet article aborde les particularités des images de sceaux byzantins et comment les algorithmes de réseaux neuronaux doivent être adaptés pour faciliter leur analyse. Nous discutons également des défis, des opportunités et du potentiel de combiner différentes méthodes d’intelligence artificielle pour analyser les sceaux byzantins.

1. Introduction

§ 1 Byzantine seals are small objects, but they bear important historical information. They contain family names, geographical data, honorary titles, offices (for example, judges, military officers, or civil servants working in different sections of the Byzantine administration), as well as dignitaries serving the church. By their number (around 80,000 surviving seals), they are the largest source of information for the prosopography of the Byzantine Empire. Before and after the period of Iconoclasm (eighth to ninth centuries), they also often bore religious iconography and revealed preferences or habits concerning the cult of saints.

§ 2 Byzantine seals represent an interesting challenge from both a historical and a computer vision perspective. From a historical point of view, analyzing a seal requires: (i) a strong understanding of the Byzantine administration and its evolution through the centuries, (ii) some familiarity with the abbreviations used on seals, and (iii) deep knowledge of Byzantine Greek. Imperial seals for official documents were made of gold, but most of these seals have been melted and are lost to us, with few exceptions. The seals preserved in museums or private collections are mostly made of lead, a material that is often corroded. Therefore, the corrosion and missing parts often make their text or iconography hardly decipherable, even for experts in Byzantine Studies.

§ 3 From a computer vision perspective, Byzantine seals are difficult to analyze since the nature, size, material, and preservation conditions represent a unique and additional challenge to overcome. Even if Byzantine seals share iconographic themes, formulae, and terminology, their crafting and complexity vary. Byzantine seals are: (i) damaged with missing parts, (ii) often corroded, (iii) with a monochrome colour palette (contrary to modern high-resolution images), and iv) the relief determines the letters and symbols (however, surfaces are generally severely damaged). It is well known that neural network algorithms generally need large datasets for training and testing (Samek et al. 2021). However, when dealing with ancient artifacts such as Byzantine seals, the reduced number of instances and the challenging characteristics mentioned before require adapting the algorithms.

§ 4 There is no literature on applying artificial intelligence (AI) algorithms to analyze Byzantine seals. However, recent breakthroughs in image-understanding algorithms applied to cultural heritage data foster our research on Byzantine seals (Aouinti et al. 2022; Eyharabide, Bekkouch, and Constantin 2021; Granell et al. 2018). This paper addresses the specificities of Byzantine seal images and how neural network algorithms must be adapted to help with their analysis. We also discuss the challenges, opportunities, and potential of combining different artificial intelligence methods to analyze Byzantine seals. Finally, we present the results of the ongoing project BHAI (Eyharabide 2024). The goal of this research is to (i) work on the recognition of writings on seals, (ii) analyze iconographic scenes, and (iii) propose solutions based on hybrid AI techniques to interpret corroded areas based on existing insights. We hope that artificial intelligence, with the training of neural networks based on a large database of already published seals, will help propose hypotheses for the missing parts of damaged seals. We are convinced that image-understanding algorithms may be valuable for historians, especially in providing evidence to verify their hypotheses and reducing search time. The clustering of Byzantine seals with similar characteristics, text and iconographic scene recognition, and semantic analysis are just a few tasks that artificial intelligence may help.

2. State of the art concerning Byzantine sigillography ground truth datasets

§ 5 Byzantine sigillography emerged in the nineteenth century as a discipline that examines the seals used in the Byzantine Empire (fourth to fifteenth centuries). The scientific study of seals started with Gustave Schlumberger in 1884, and it continued during the twentieth century, with scholars such as Vitalien Laurent (1896–1973) in France and George Zacos (1911–1983) in Istanbul and later in Switzerland (Cheynet 2008; Cheynet, Bulgurlu, and Gökyıldırım 2012). The number of seals discovered so far is around 80,000. This number increases by 1,000–1,500 each year after excavations or the use of metal detectors, mainly in former regions of the Byzantine world. Many appear online to be sold at auction houses.

§ 6 Large collections of seals are preserved in the following museums or institutions: 17,000 at Dumbarton Oaks (Washington DC), 12,000 at the Hermitage Museum (Saint-Petersburg), around 10,000 seals in Paris, mainly at the Cabinet des Médailles (BnF), 6,328 in the former Zacos collection, 413 in the former Seyrig collection, ca. 800 from older collections, ca. 1,500 seals at IFEB (Institut Français des Études Byzantines), and the rest in private collections. Other museums in Europe also hold Byzantine seals in their collections. The Numismatic Museum at Athens, for example, holds ca. 2,500 seals. In 2009, Ivan Jordanov published 3,200 seals discovered in Bulgaria and preserved in different collections, including 600 at the Regional Historical Museum of Shumen (Jordanov and Zhekova 2007). The Istanbul Archaeological Museum holds ca. 2,000 seals published in 2012 (Cheynet, Bulgurlu, and Gökyıldırım 2012). There are also numerous unpublished private and public collections; others have been published recently. For example, the Tatış collection of 450 seals in Turkey was published in 2019 (Cheynet 2019).

§ 7 A significant open-access database of Byzantine seals is maintained at Dumbarton Oaks in Washington DC, USA. All other collections are only available in paper publications. A project to gather Byzantine seals in one extensive online database was proposed as SigiDoc in 2010 on the model of EpiDoc using XML encoding (on this topic, see Sopracasa et al. 2024, this volume). Based on SigiDoc and interoperability concepts, the project DigiByzSeal aims to create a centralized hub for Byzantine Sigillography. This project focuses on text encoding and data models for the digital edition of Byzantine seals. Also, the project DiBS aims to valorize and strengthen Byzantine Studies by advancing a cluster of four Byzantine auxiliary disciplines—Sigillography, Numismatics, Epigraphy, and Greek Manuscript Studies (on this topic, see Drach et al. 2024, this volume). In France, Laurent Hablot has set up a database of medieval seals kept in French institutions called Sigilla (on this topic, see Hablot 2024, this volume). This database has 54,786 medieval Latin seals but none regarding the Byzantine Empire. In Great Britain, a similar database has emerged for medieval seals preserved in the British Isles called DigiSig (on this topic, see McEwan et al. 2024, this volume).

§ 8 The collections mentioned before can be used as ground truth, which refers to the data from the real world used to train and evaluate the outputs of AI models. Ground truth data is essential for artificial intelligence. To our knowledge, no artificial intelligence project has been proposed on Byzantine seal datasets. Even more, there is no AI method for interpreting and reasoning about iconographical representations of Byzantine seals.

3. New challenges when combining AI and sigillography

§ 9 Byzantine sigillography can benefit from using AI methods. However, their implementation is not that straightforward. There are several drawbacks to overcome first. In this section, we present those challenges and propose some solutions to solve them.

3.1 No unified knowledge database regarding Byzantine sigillography

§ 10 Although around 80,000 seals have been unearthed and preserved in public or private collections worldwide, there is no unified knowledge database regarding Byzantine sigillography. Moreover, there is no interoperable and annotated ground truth dataset of Byzantine seals. However, the organization, integration, and annotation of sigillographic data are challenging since images and textual descriptions detailing the seals are dispersed worldwide.

3.2 Difficulties to homogenize heterogeneous and scattered data

§ 11 As mentioned before, several collections of seals exist worldwide. Each collection is preserved using different methods, recorded using different metadata, and following different standards. Therefore, another drawback may be homogenizing dissimilar and scattered data (descriptions in different natural languages) and images (different formats, resolutions, and views) among several collections. The SigiDoc initiative, the first EpiDoc extension to Byzantine seals based on XML and TEI-compliant, is under development.

3.3 Agreeing on a validation protocol and metrics

§ 12 Ground truth data annotations are humanly provided classifications of the data on which AI algorithms are trained or against which they are evaluated. Since the seals are generally damaged or incomplete, domain experts sometimes disagree in their interpretation and, consequently, in their annotations. Therefore, defining validation metrics to qualify and verify the annotations is vital. Another challenge will be agreeing on a validation protocol and metrics to evaluate the manual annotations (intra- and inter-annotator agreements).

3.4 Legal issues since copyright may protect some images

§ 13 A potential drawback could be legal issues since copyright may protect some images. Legal problems may arise if the protected work is shared, used, or reproduced. We should first ask permission from the copyright holder when dealing with copyrightable works.

3.5 No IT tool capable of guiding or assisting the users in the recognition of iconographic scenes

§ 14 The analysis and interpretation of Byzantine seals is a complex task requiring expert knowledge of Byzantine sigillography and Byzantine Studies. For example, on a damaged seal, the presence of a character with a nimbus, sword, and wings could suggest that it is Saint Michael. Also, a custom (but by no means a rule) in the Byzantine Empire was to represent the saint corresponding to the owner’s name on his seal. Thus, the seal owner representing St. Michael was probably named Michael. Currently, no tool can guide or assist the experts or students of Byzantine studies while analyzing the seals.

3.6 Need to interpret the seal as a whole and not as isolated parts

§ 15 Domain experts generally understand iconographic scenes after identifying several objects and their relations, for example, by recognizing imperial objects in the hands of emperors and empresses, as well as the specific crowns or clothing they wore. Seals bearing religious figures also follow specific iconographic characteristics. Therefore, it is necessary not only to identify each element (such as crosses, crowns, swords, etc.) but also to put them in context and in relation to each other to understand the whole scene in a seal. Even more, the figures and scenes need to be studied, as well as the object relations within a seal (such as the Virgin Mary holding the Child, a patriarchal cross mounted on three steps). In addition, the relations between different seals (such as belonging to the same owner or containing the same figure or inscription) may also be analyzed.

3.7 Advanced natural language processing (NLP) techniques to deal with different languages

§ 16 Another central point in the study of Byzantine seals is the recognition of characters and inscriptions. Most of the preserved seals contain inscriptions in Greek, but there are also writings in Arabic, Armenian, Latin, and Syriac, among others, although in smaller quantities. Processing natural language inscriptions in different languages requires advanced NLP techniques.

3.8 Lack of data for training

§ 17 One common barrier to using deep learning to solve problems is the amount of data needed to train a model. The quality, quantity, and variability of the available images could run into some difficulties when data for training is lacking. Object and character recognition in ancient artworks is challenging since the samples for training neural networks are relatively small. To overcome this drawback, domain adaptation approaches, and other transfer learning techniques can be applied to reuse well-known datasets for training.

3.9 Consider the changes in dignities and functions over time

§ 18 Clustering seals with similar characteristics and/or belonging to owners with the same dignity and function may help the experts analyze them. The study of the similarities and differences among the resulting clusters of seals may formulate new hypotheses in the humanities. For example, grouping seals belonging to the same owner may improve the hypotheses concerning Byzantine prosopography and help reconstitute family networks.

§ 19 However, the Byzantine Empire had a complex system of bureaucracy. During the more than a thousand years of the empire's existence, several dignities and functions were created and abolished, and many lost or gained prestige. Honorary titles also change with time, creating new titles to single out members of the imperial family. Therefore, it is important to consider the changes in the administration, the administrative geography, the dignities, the functions, or the iconographic motifs over time.

3.10 Consider the seals' deterioration level

§ 20 Seals are used to authenticate letters and documents. Generally, they were secured so the document could not be opened without damaging the seal. This is the reason why most of the preserved seals are damaged or partially incomplete. As mentioned before, the objects and figures depicted in seals are used to determine the period of their creation. However, when a seal is damaged or partially destroyed, it is difficult to identify its content. Thus, it is not always possible to estimate the inception date.

3.11 An area of fragility in the middle

§ 21 Seals are hollow in their centre to leave a passage for the thread used to attach the seal to the document, thus creating an area of fragility along this line. Several seals are broken in the centre or have missing parts. There are even seals that are divided into two or more parts. An additional challenge arises when the motifs or patterns to be identified are not complete.

3.12 Information not imprinted in off-centre seals

§ 22 Byzantine seals are made using a blank (i.e., a round piece of lead struck with a clamp bearing text and image engraved, usually in reverse, on the two internal sides). Blanks are produced in prepared molds in different but often standardized sizes. If a person wants to strike a seal, it is necessary to find a blank. Sometimes, the engraving is larger than the blank (or the blank is not centred), and part of the message is not imprinted on the seal. Sometimes, the opposite is true: when the blank is larger, a margin appears between the imprinted message and the border of the blank.

4. BHAI project: Current research and results

§ 23 The BHAI project is an ongoing project funded by the French National Research Agency (ANR) that will end in 2025. This Digital Humanities project proposes an innovative approach to artificial intelligence applied to Byzantine sigillography. Our proposal combines computer vision, knowledge engineering, and mathematical modelling of spatial relationships to help interpret Byzantine seals (iconography and writings). In this section, we briefly review the articles that have already been published, present preliminary results obtained in the ongoing research, and discuss future research.

§ 24 As mentioned, one of our goals is to transcribe the text in the seals. However, we cannot use traditional optical character recognition (OCR) approaches since there is little contrast between the characters and the background. In contrast to contemporary writing methods, which rely on a noticeable difference in colour between the ink and the paper, the characters in the seals are engraved in relief. In addition, since Byzantine seals are mostly made of lead, they suffer from corrosion and are often damaged. Therefore, their reading is challenging because some seals have been crushed or shattered, making their inscriptions difficult or impossible to read. We proposed an approach based on deep learning to read seal characters and provide a transcript at different transcription levels, plain text, and restored text (including hidden text because of lack of room or damaged text). Our approach perceives characters from shades. Since we have few annotated images, we opted for a two-step approach: to localize and then to recognize the characters (Eyharabide et al. 2023).

§ 25 Other research carried out in this project is the study done by Lucia Maria Orlandi (Orlandi 2022). She conducted a chronological examination of the sizes of seals used by the *ekklesiekdikoi,* the judges of the ecclesiastical tribunal of the Church of Hagia Sophia in Constantinople, and other ecclesiastical officers of the patriarchal court. The idea was to establish connections between seal dimensions and their historical context. The study utilizes a quantitative approach, conducting statistical analysis on a sample of seals sourced from various collections and corpora already extensively used by the BHAI project for algorithm training. The evolution of the diameter of the *ekklisiekdikoi* seals through the centuries has been assessed against the historical context. During the twelfth century, the *ekklisiekdikoi* seals increased their diameter dramatically, more than any other known seal, to emphasize the institution's significance against attempts from the imperial authority and the patriarchal court to limit their autonomy and prerogatives.

§ 26 The BHAI project also aims to interpret Byzantine seals using spatial relations. We are convinced that the arrangement of personages and objects in space provides valuable insights for their interpretation. First, we determine the central personage (or object) by computing the covering area of several personages (or objects) since the central element is often the biggest. Then, we calculate the directional relations of other objects and the central personage. In other words, we want to know if a particular object is on the left, right, above, or below the central person or object (Eyharabide et al. 2024).

4.1 Segmentation and image annotation

§ 27 The first objective of the BHAI project is to create a curated and annotated dataset of Byzantine seals. Byzantine experts manually curated and annotated the images to build ground truth datasets. Building a corpus of annotated images is vital for training and evaluating AI algorithms.

§ 28 Two types of new data are produced from the images collected: manual annotations of the images and transcription of the texts on the seals. The type of annotation on the images depends on the algorithm used and the desired goal:

- **Image classification**: The annotation is simply a label within a predefined list. In our case, each image is labelled with the estimated date of the seal (e.g., "10th century" or "11th century"), place of provenance, dignities, and functions of the bearer.
- **Object detection**: Annotation provides the position of objects in the image with a "bounding box," a rectangle containing the object.
- **Instance segmentation**: Annotation consists of precisely outlining objects. It is the most precise annotation but the most time-consuming and tedious to perform manually.

We chose instance segmentation because it produces better and more reliable data for training, which can sometimes compensate for the limited data. Using Supervisely (Supervisely OÜ 2024), we obtain a set of points for each annotated object that constitutes the bounding polygon. From the polygons, we automatically produce bounding boxes for object detection. Regarding the labels used, we consider the types of virgins, the type of prayer, and the centuries divided into four parts. Regarding the iconography elements, we consider different types of crosses, nimbus, and persons (such as Jesus, the Virgin Mary, St. Nicholas, etc.). We also annotate objects and body parts (wings, hands, beards, etc.).

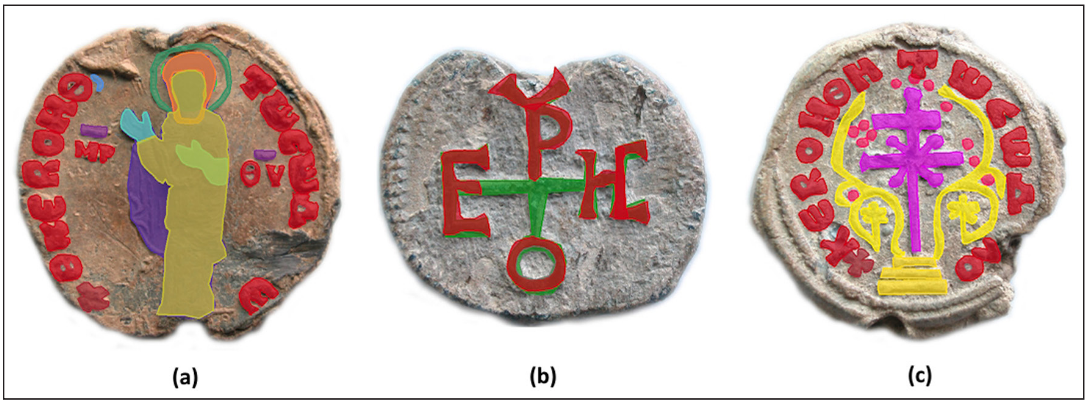

Figure 1: Three examples of annotated seals.

§ 29 **Figure 1** shows three examples of annotated seals in the Tatış collection: (a) The Virgin Mary surrounded by text, (b) Greek characters and a cruciform monogram, and (c) a stepped patriarchal cross with tendrils and text. Regarding the inscriptions on the seals, we annotated not only all the Greek characters from the Unicode standard, but also the diacritics from Athena Ruby's font. For some characters, we also consider variations over time, such as the character *beta*. The letter *beta* had several highly divergent forms. In the seals, we consider two variants: B and R = βῆτα. It is important to notice that we annotated the monogram as a whole and each character separately. In summary, each annotated object can be exported as a mask for semantic segmentation. In the end, we have (a) the original image, (b) the annotation in JSON format, (c) the human masks for visualization (where each pixel has the colour of the corresponding class), and (d) the machine masks.

4.2 Detecting visual elements using deep neural networks

§ 30 One objective of the BHAI project is to analyze the iconographic scenes (objects and personages). Therefore, we used deep neural networks to detect different types of crosses and cruciform monograms to reach that goal. Christianity was the official religion in Byzantium, and the emblem of Christianity is the cross, which symbolizes the crucifixion of Jesus Christ. Thus, we decided to identify crosses as the first attempt to analyze Byzantine seal content. During the later phase of the Iconoclasm, crosses began to appear massively on monograms. Even after the end of this period, crosses were still preferred for a long time, especially at the hierarchy's lowest levels. In the early ninth century, seals adorned with potent crosses were often seen. However, patriarchal crosses (often accompanied by tendrils on the sides) are typically found throughout the late ninth and early tenth centuries (Cheynet 2008).

§ 31 Monograms are like puzzles, and the Byzantines loved them. They create monograms by combining the letters from their baptismal or family names. Every letter of a name must be included, with the possibility of repetition and combination between letters. Monograms can be either block or cruciform. In this article, we are interested in cruciform monograms since they are compositions of letters around and on the branches of a Greek cross. Due to the resemblance of these monograms to crosses, we decided to detect them together. **Figure 2** presents some preliminary results.

§ 32 We trained neural networks to detect monograms and different types of crosses using YOLOv8 (Jocher, Chaurasia, and Qiu 2023). It is important to note that the algorithm detects those elements even when the seals are damaged. Byzantine seals have different degrees of deterioration. While many seals are in good condition, others are damaged but still interpretable, and others are so broken or harmed that not even experts can read them.

§ 33 Deep learning techniques are an excellent tool for historians, and several works have successfully used them on images of historical elements (Eyharabide et al. 2023; Rahal, Vögtlin, and Ingold 2023; Rezanezhad, Baierer, and Neudecker 2023).

Iconographic elements are an interesting application field for the image segmentation domain. Image recognition techniques can be used to automatically identify some visual characteristics, helping sigillographers in the classification or dating of seals.

Figure 2: Examples of crosses and cruciform monograms detected in Byzantine seals.

5. Perspectives and future research

§ 34 In the near future, we will explore other approaches based on artificial intelligence to analyze Byzantine seals from another point of view. The idea is to combine different AI methods to prove some already known hypotheses but also some new hypotheses (such as finding evidence that the combination of a type of cross and a particular inscription is more frequent in a certain period). This section presents some perspectives and future research on the BHAI project.

5.1 Exploring Byzantium via Byzantine monograms

§ 35 Byzantine monograms are often very difficult to interpret, in particular, because there seems to be no rule for the composition and arrangement of the letters. These letter combinations correspond to a creative process that varies drastically depending on the artisan's inspiration or the owner's preferences. There are no predefined guidelines for the creation of monograms. Therefore, many monograms are still undecrypted.

§ 36 Artificial intelligence has the potential to enhance the decryption of monograms significantly. However, deciphering monograms can be challenging, mainly because of the absence of a standardized guideline for the structure and placement of the letters. From a computational point of view, monograms constitute a fascinating object to study because they include a certain degree of combinations that must be compared with onomastic lists. Indeed, when it comes to first names, we can refer to the known elements of onomastics, but it is more complicated regarding last names. Therefore, an element of probability must be considered, leading to an analysis of the linguistic characteristics of onomastics (regions, periods). Based on the preliminary results presented in the previous section, we plan to further explore the monograms on seals. The idea is to develop a semi-automatic tool to help experts read monograms.

5.2 Semantic graphs for representing Byzantine sigillographic data

§ 37 Recently, a growing number of works have used AI techniques applied to graphs to study interconnected data (Devi and Kasireddy 2019). These recent works in graph analysis, especially social network analysis, allow us to apply its methods to other data types, such as historical networks. To our knowledge, few works apply graph theory and formal network analysis methods to studying relationships between historical data, such as that of Byzantine seals.

§ 38 The iconography and inscriptions of Byzantine seals offer unique insights into the social and political elites of the Byzantine Empire. In our future work, we propose representing the relationships between the seals in semantic networks, which are well attested but not yet represented as knowledge graphs (KG). The objective is to model the relationships between seals, people, institutions, and functions to represent the common characteristics and the family, professional, religious, and political ties that united them. The idea is to establish a visual representation of seals, highlighting the roles of elites, politics, and religion in the Byzantine Empire. The characters, objects, legends, and inscriptions continue to be vital for knowing dignities, titles, and functions. In addition, we have other sources of information such as diameter, weight, or colour, which provide clues regarding the hierarchy, career progression, professions, selection processes, and, most importantly, the Byzantine elites' family, social, and political ties.

§ 39 By analyzing the relations among seals, we can find crucial evidence for describing a person's professional trajectory, analyzing a family tree, or verifying a person's presence in a specific location or period. Also, the invocations or prayers in the inscriptions are combined with a wide variety of iconography. These elements collectively convey personal devotion and reveal the religious preference within a community.

§ 40 In this context, several graph analysis methods, such as community detection, can be applied to discover seals that share common characteristics and are closely connected. Other metrics like centrality indicators can be used to identify the most influential people or analyze how the seals' owners are interconnected in the network using information diffusion techniques in graphs. Thus, we aim to offer new perspectives on a research area mainly dominated by more traditional statistical and prosopographic studies and, at the same time, provide a powerful tool for analysis and visualization.

6. Conclusions

§ 41 Sigillography emerged in the late nineteenth century, and despite its relatively small number of specialists compared to other historical sciences, it is currently thriving. The combination of years of knowledge in sigillography and new AI techniques can accomplish enormous breakthroughs in this area. Nowadays, the impressive achievements of deep learning algorithms could facilitate substantial progress in creating, organizing, and utilizing seals' image datasets.

§ 42 This article analyzed the trends, challenges, and perspectives of applying AI to Byzantine sigillography. We presented some ongoing research on the BHAI project. The results are encouraging, but more work still needs to be done. However, to our knowledge, no other AI-based project has been suggested for Byzantine seal datasets. We firmly believe that AI has the potential to considerably assist in introducing students to sigillography and help experts in their research.

§ 43 By the end of the BHAI project, we expect to offer a tool to aid in the reading and dating of Byzantine seals. Putting the shape of the letters and some aspects of the decor in a series makes it possible to refine the proposed date. A more detailed dating may improve the hypotheses formulated by historians concerning the Byzantine prosopography (the reconstitution of the Byzantine aristocratic families, civil servants, and clerics) and the changes in the administration, the administrative geography, or the iconographic motifs retained. Our project's originality is applied to Greek letters and religious images from the Byzantine world, but the method used can be extended to objects inscribed in Latin characters or other alphabets.

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Competing interests

The author has no competing interests to declare.

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