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Mechanisms and applications of clay barriers for sealing masonry

Earth is one of the oldest waterproofing materials used in construction. Archaeological evidence around the world suggests that earth was used to seal hydrological systems as far back as the Neolithic period (Mays et al. 2013; Warren 1998, p. 175; Kirke 1980; O'Brien et al. 1980). So-called puddled clay was used extensively in civil engineering in the early industrial era as a waterproof lining for British canal constructions in the 18th and 19th centuries (Reeves et al. 2006, p. 377). In semi-arid climates, buildings are traditionally protected against precipitation by sealing flat roofs with compacted earth (Warren 1998). Archaeological evidence of such constructions dates back to at least the early Byzantine Empire during the 4th century, where an underlay of woven reeds was covered with a layer of earth as waterproofing (Isler 2013). The existing literature details sealing materials and methods such as *Huwwar*, a calcareous clay mortar from the southern Levant (Parker and Betlyon 2006, p. 173; Rollefson 1996, p. 223; Wright 1970), as well as *Arga* and *Markalak*, clay and calcareous rocks and soils from Tibet (Feiglstorfer 2020; Weisskopf 2011; Alexander 2005). Earth flat roofs are still common in the Orient today and consist of relatively clay-rich straw-earth packs that are regularly re-compacted with roller-like stones for maintenance to close cracks (Fig. 1). The *Dornschen Lehmdächer* from the first half of the 19th century represent a less successful attempt to use earth as a sealing material for German flat roofs in early industrialisation: clay was mixed with tar, pitch and sand to create an impermeable layer, but they were rarely durable in the long term (Conradi 1842, p.12) and the method was soon replaced as bitumen and poured asphalt techniques became available. Unlike the waterproofing of roofs, masonry waterproofing has a relatively recent history (Maier 2012). In the past, damp cellars were often simply tolerated and the function of the space

01 Flat earth roof in the Kozi Abdurasal Mosque in Samarkand, Uzbekistan (19th century). An approx. 10 cm thick layer of clay was applied on a straw mat with wooden boarding beneath and has now completely dried out under a modern corrugated iron roof. The introduction of modern building materials to the historical building fabric has led to the neglect of the traditional flat earth roofs. Photos from 2013.

02 Retroactive masonry waterproofing at the Heilige Geist Church, Teupitz (13th/14th century). A vertical barrier was inserted in 2008 using local glacial till (left photo, by T. Wondoll). The density of the waterproofing layer was checked in 2014 and found to be functional (Michette 2015) (right photo).

was chosen accordingly. Nevertheless, there is sporadic evidence of clay-based masonry waterproofing in historical buildings. In the Jingganshan region of China, calcareous soil was mixed with nut oil to produce sealing compounds for moisture barriers (Dai 2013). The use of compacted layers of clay-rich earth as a barrier layer has been documented in a few earth buildings in Saxony, Germany, from the 18th and 19th centuries, but also in earlier buildings dating back to the 6th to 8th century (Ziegert 2003). But with the advent of industrially manufactured bitumen products and water impervious concrete in the early 20th century, the relevance of clay barrier layers began to wane. In civil engineering, especially in hydraulic engineering and landfill construction, clay barriers continue to serve a purpose as sealing systems against pressing water or landfill leachates. For the latter, the capacity of clay minerals to bind pollutants through cation exchange and retention provides an additional degree of protection against the escape of pollutants. The emergence of bentonite panels in the last 50 years and specialised clay barrier mixtures in the last 20 years are evidence of the increasing industrial production of clay-based waterproofing materials for a wider market. Furthermore, individual projects have showcased the use of appropriate, naturally occurring clay-rich earth for waterproofing, for example at the Heilige-Geist Church in Teupitz, Brandenburg where local natural soil (till) was applied as a vertical barrier (Fig. 2). This last variant is an example of an approach that, unlike conventional energy-intensive methods, is practically energy-neutral over its entire life cycle. A further advantage in the context of the preservation of historical monuments is that the retroactive application of earth waterproofing requires no chemical or mechanical means of bonding and is completely reversible.

Clay-based waterproofing is a construction method which is not covered in the building codes. It is not addressed in the relevant norms and standards on the waterproofing of buildings and it is also not listed among the earth building materials and construction methods described in the German *Lehmbau Regeln* (Dachverband Lehm 2009). In technical literature on earth building, too, little mention is made of clay-based building waterproofing materials (Röhlen and Ziegert 2020). In terms of the trades, waterproofing buildings is regarded as belonging to the realm of building construction and not civil engineering. With the exception of bentonite panels, very few studies have been undertaken of applications in the building sector, and there is correspondingly little in the literature. Suitability tests for different specialised sealing mixtures and naturally occurring clays are, however, widely available due to their widespread use as a barrier in contaminated sites. These demonstrate the general impermeability of the building material (Gartung et al. 1993). The intention of this paper is to provide an overview of the composition and application of clay-based masonry waterproofing. It also examines the physical mechanisms of clay-based mixtures as moisture barriers at the base of buildings through a series of tests which are described in detail in Michette (2015) and Michette et al. (2017).

Bentonite panels

Bentonite panels or mats are a composite product comprised of pure, highly swelling bentonite powder encapsulated in a casing of corrugated cardboard or geotextile membrane. Typically, they are only a few cm thick. At present, bentonite panels are the only clay-based waterproofing products described and investigated in detail in the technical literature (Cziesielski 2001). At the beginning of the 1980s, they were accorded general approval status by the German Technical Approval Authority DIBt (No. Z 27.2-101) but that has since expired and has not been extended. Bentonite panels are therefore not a generally approved construction method and their use requires express approval from the client. Since then, however, many years of practical building experience have been gained (Egloffstein 2009). The panels or mats are installed dry on the surfaces to be waterproofed and pressed in place with soil. The surfaces must be free of ridges and holes and the panels must be protected against coarse, sharp-edged material, e.g. by using a protective fleece. The waterproofing layer should not be subject to shear forces. When they absorb water, the clay minerals delaminate and peptise, reducing permeability through the material. In combination with PVC foils, a high diffusion resistance can also be achieved. When installed, sodium bentonite mats achieve permeability coefficients of k_f = approx. 3×10^{-11} to 5×10^{-11} m/s. After installation, an ion exchange from sodium to calcium takes place over a timespan of several months up to a few years and a long-term permeability coefficient of k_f = approx. 1×10^{-10} to 5×10^{-10} m/s is achieved (Egloffstein 2009). Where water has a high salt content, its compatibility with bentonite must be assessed. If the use of bentonite is possible, initial swelling should be carried out using water with low electrolyte levels. To ensure they are always subject to moisture and thus to continuous swelling pressure so that they cannot form cracks, bentonite panels should only be used where they are subject to constant water pressure.

Clay barrier material

Clay barrier materials are comprised of clays or clayey soils which are compacted adjacent to building foundations to protect against ground moisture intrusion. They function according to the same principle as clay barriers in landfill, contaminated land and pond sealing. There is evidence of their use on individual historical structures. Clay barrier materials can be further subdivided into:

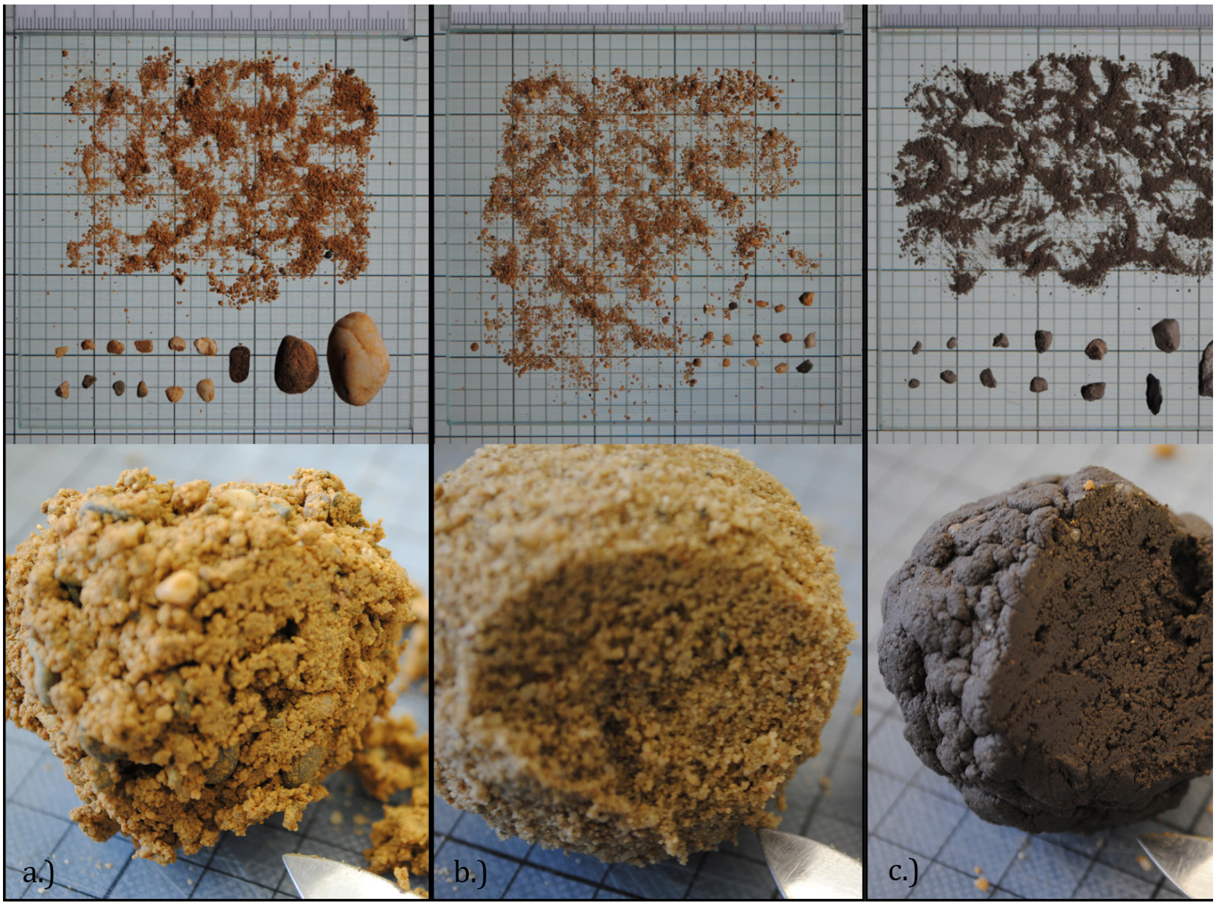
- Waterproof clays are naturally occurring soils with a certain composition which are well suited for waterproofing tasks with little or no further treatment.
- Specialised clay-based mixtures are prefabricated mixtures of different soil components which are specially optimised for sealing applications. Following long-term use as landfill and contaminated repository liners, clay-based sealing mixtures have been occasionally used in the construction industry over the last 15 to 20 years and are now slowly gaining traction (e.g. Preuschen 2009).

Both methods are underrepresented in the technical building literature. Neither method is a generally approved construction method and their use requires express approval from the client.

Composition and effect

In Michette et al. (2017), three commercially available clay-based sealing barriers were analysed: two industrially produced mixtures and one unmodified glacial till from the Saxony region of Germany (Fig. 3). The test series was not intended to test the suitability of the materials as clay barriers or to classify them. The water permeability coefficient and various durability tests had already been determined in other tests, and all three products have been employed successfully in the past for damp-proofing applications, so are generally suitable for waterproofing masonry in appropriate situations. The purpose of the laboratory tests was to determine the specific mechanisms by which these products achieve low hydraulic conductivity with a view to revealing the differences between the specialised mixtures and the naturally occurring till, and ultimately to draw conclusions about the range of general applications of clay barrier material.

Standardised test methods from soil science were used to investigate the composition and sealing effect of the specimens. The test methods and setup followed that of existing suitability tests used for landfill barriers, facilitating better comparison and possible synergies with the already extensive landfill engineering work. The tests included classification of the soil type (DIN 18196), determination of the grain size distribution (DIN 18123), the Proctor density and optimum moisture content (DIN 18127) and the Atterberg limits (DIN 18122). From the grain size distribution, one can mathematically approximate the permeability coefficients (Beyer 1964), however these



03 Tested materials. Top dry grains; bottom moist mass. a Mixture A, b Mixture B, c Saxonian till (from Michette et al., 2017).

calculations are based on grain packings and do not take swelling or sorption properties into account. The lime content was determined in accordance with DIN 18129 according to Minke (2012) and the water mass adsorptivity according to DIN 18132 using an Enslin-Neff apparatus. From this one can draw conclusions about the type of clay minerals. Swelling-induced heave was determined according to Madsen and Mueller-Vonmoos (1989). Examining the heave in combination with knowledge of the condition and composition of the sealants provides insights into the internal mechanism of the sealant, e.g. whether crystalline or osmotic swelling occurs. An overview of the test results can be found in Table 1.

The sealing effect of the clay-based sealants investigated is the product of several mechanisms acting partly in combination. Here we can observe clear differences between the till and the specialised mixtures. The industrially produced mixtures are similar in their mineral composition and consist of approximately 90% sand or gravel, 10% clay and very little silt. Both grain size distribution curves follow an approximate Fuller parabola for optimum compactability. Both mixtures have a high to very high water absorption capacity, which indicates highly swelling sodium smectites in the clay fraction.

The composition of the till, on the other hand, is clearly distinguishable from that of the mixtures. The grain size distribution exhibits a much higher proportion of fine grains, and the fines consist mainly of silt. Nevertheless, a higher clay content was found in the till than in the factory produced mixtures. The water absorption capacity is, however, considerably lower and suggests a slightly plastic, malleable clay. It is also contains a considerable amount of lime.

Due to their favourable grain size distribution, the specialised mixtures can achieve a high density and water resistance through compression alone without considering the other mechanisms. An optimum mixture has a grain distribution that allows the particles to pack together as densely as possible: progressively finer particles fill the pore space between the coarser aggregate. A certain optimum moisture content will be necessary in order to achieve Proctor compaction (maximum density of consolidated grains). The clay

Table 1: Overview of the test results

	Mixture A	**Mixture B**	**Saxonian till**
Clay fraction (M%)	9	7	14
Coarse fraction (M%)	88	91	54
Calculated conductivity k_{fx} (m/s)	1×10^{-5}	1×10^{-4}	8.5×10^{-9}
Measured conductivity k_f (m/s)*	8.5×10^{-11}	5×10^{-10}	8.5×10^{-11}
Proctor compaction ρ_{PR} (g/cm³)	2.09	1.76	2.00
Opt. moisture w_{PR} (%)	8.6	17.2**	9.0
Opt. moisture (% total mass; d < 0.04 mm)	24	47	11
97% dry moisture $w_{PR0.097}$ (% total mass d < 0.04 mm)	20	27	–
Shrinkage limit w_S (% total mass; d < 0.04 mm)	25	37	15
Water adsorption w_A (% total mass; d < 0.04 mm)	≥ 145	≥ 218	44
Swelling deformation (%)	5.9	0.8	1
Duration until maximum swelling deformation (h)	360	168	48

**Permeability coefficient taken from product information sheet.*

***The water content on delivery is 7% and allows a Proctor density of 97% dry.*

minerals within the mixture have the capacity to bind large amounts of water, in turn retarding the flow rate of water trying to pass through the layer. This mechanism also retains moisture when drying out, and if the clay content is too high, there is a risk of irreversible cracks forming in the mineral framework during drying phases. The adsorption capacity of the clay minerals also has the ability to further constrict pore space as the clay minerals expand. In naturally occurring clays, this effect may be rather small. The moisture present in the barrier material during installation already activates several crystalline swelling stages of the mixed clay minerals, and the calculated permeability coefficient and the measured permeability coefficient differ by only a few orders of magnitude (Table 1). In the case of the industrially produced mixtures, the controlled addition of sodium smectite may be the main contributing factor for the sealing effect. The reason for this is the much greater and longer-lasting osmotic swelling that takes place in compacted layers (Madsen and Mueller-Vonmoos 1989). The sealing effect is a caused by peptising of the clay-water system in the pore structure of the mass – osmotic swelling – after the otherwise sandy material has been compacted.

The swelling expansion ("heave") of the two industrially produced mixtures differs considerably. Despite the similar composition and characteristics of the clay minerals they contain, a considerable heave of 5.9 % was measured for mixture A and only 0.75 % for mixture B. One reason for this may be the lower Proctor density or the higher porosity of mixture B. It is possible that the clay proportion has been adjusted so that it closes only the remaining macropores when activated without exerting any further pressure on the remaining mineral framework. It is not essential to absolutely supress swelling to ensure the sealing effect (Yong 1999): with a certain level of counter-pressure, the pore structure is already filled in without settlement in the mineral framework. But it is important that adjoining building elements can absorb the resulting forces, and also that excessive volumetric enlargement, which could permit a critical loosening of the mineral skeleton, should be prevented. It is also important to ensure that the clay content during the installation state has a consistency that within the moisture fluctuations of the sealing mass does not create conditions that could lead to crack formation. Prefabricated mixtures can be adjusted accordingly through the minimal addition of very active clay minerals. The moisture content during installation should not lie too far along the wet side of the Proctor curve. In the case of mixture B, the optimum water content to reach the Proctor density is above the shrinkage limit. In the factory state, however, the water content is considerably lower, allowing installation at 97% of the Proctor density. The tested barrier materials therefore exhibit high volumetric stability under optimal installation conditions: the product state is below the shrinkage limit and there is no risk of shrinkage cracking.

The sealing effect of the tested till, on the other hand, relies less on the activation of the clay minerals and more on the high density and water resistance of the compacted mass as well as the possibility of pore cement formation. Lime causes hardening processes which reduce the risk of shrinkage cracks and form pore cement (Minke 2012). Glacial till may therefore generally be well suited as a waterproofing clay due to its high lime content and graded grain size distribution of rounded grains. Historical and traditional clay-based masonry waterproofing methods also often have a high lime or calcite content; while it is naturally present in Tibetan *Markalak* (Feiglstorfer 2020), in the case of the Jordanian *Huwwar* (Rollefson 1996, pp. 223) it was subsequently added.

Installation

Specialised mixtures can be installed using prefabricated commercial mixtures or on site by adding minerals to locally available clay. When preparing on site, care must be taken to ensure a homogenous mix. The same applies to excavated naturally occurring waterproof clay. In all cases, the water content at installation must be checked. As a guideline, the moisture content should make it possible to form a solid ball.

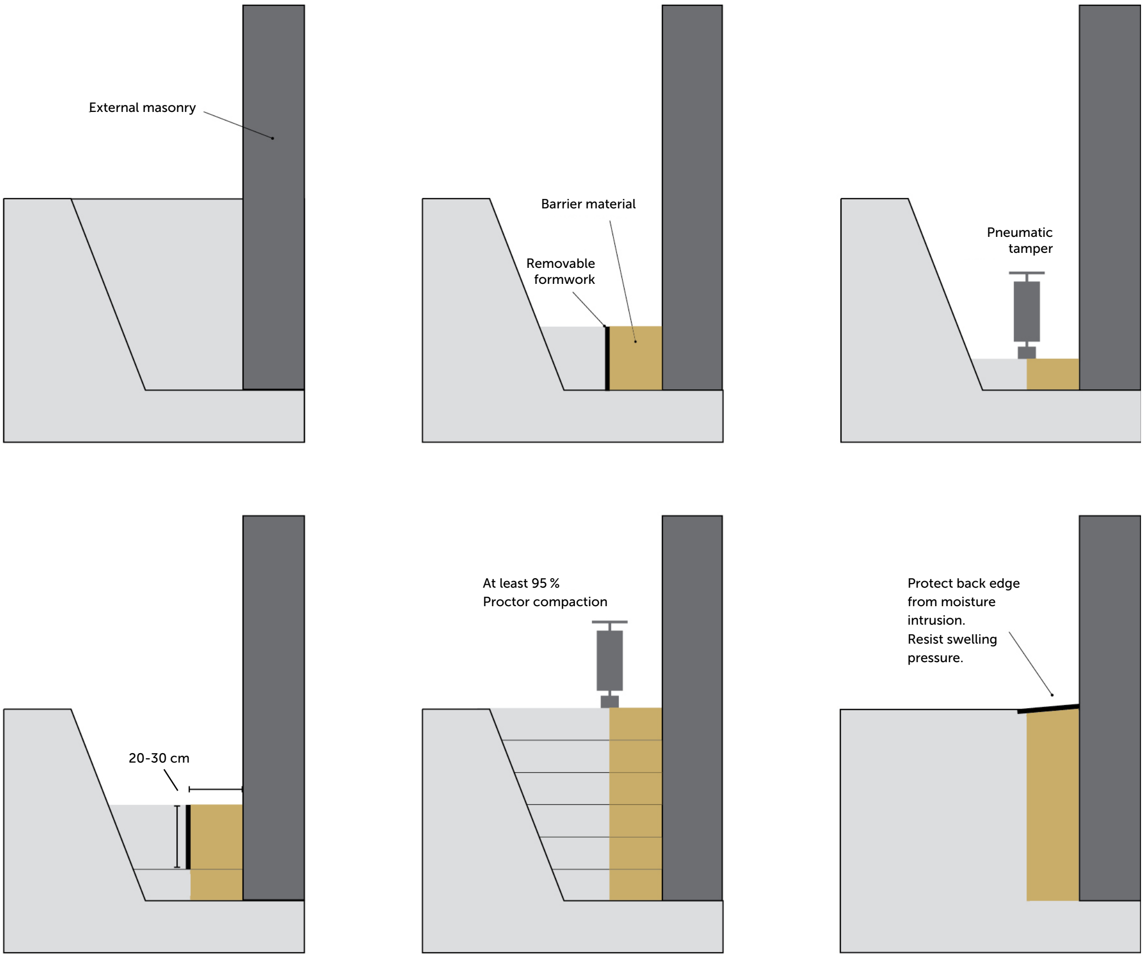
The process of installation is shown in Figure 2. As with normal waterproofing work, a working area is first excavated, and the subsoil then compacted. A strip of rigid formwork is placed parallel to the masonry wall at an even distance of 20 to 30 cm (depending on the required thickness of the waterproofing layer). The barrier material is then poured into the space between the formwork and the wall in layers of approx. 20 cm and the space behind the formwork filled with excavated material. Some manufacturers require a protective layer of gravel with a drainage at the bottom in the case of high water loads between the waterproofing and the ground. A gravel filter can offer additional protection against frost penetration and plant roots (Ludwig 1993). After each layer, the formwork is removed and the entire fill area is compacted with a mechanical or hand-operated tamper, repeating the process until the submerged section of wall is completely covered by the clay barrier. It is important to ensure that the barrier material is compacted to at least 95% to 97% Proctor density. This can be verified by taking several core drillings from the waterproofing layer during construction and checking for density and, if necessary, also the water impermeability directly. The points from which core samples were taken must be carefully re-compacted. The density can also be checked using rebound technologies (Hemker 1994). Finally, the top of the vertical clay barriers should be covered to protect against moisture intrusion. Concrete block paving, gravel and nutrient-poor soil are suitable: it must be able to direct water away from the building and, depending on the manufacturer, apply a certain load (approx. 5 kN/m^2) to the barrier material to resist swelling pressure. The adjoining building components must also be able to resist this load.

When compressing the barrier material, the installation moisture may escape. To counteract this, a sealing slurry can be applied to the wall or any wall covering layers (e.g. insulation layers). With regard to the different load cases, the manufacturer's instructions should be observed where available. Bentonite-containing specialised mixtures are generally effective against all load cases. Waterproof clays may have to be protected against constant water loads.

Outlook

The inclusion of clay-based moisture barriers in the specialist literature on earth building and the rules of earth building should be reconsidered. Clay-based waterproofing offers an interesting alternative to conventional energy-intensive methods, especially in the context of sustainable material life cycles in the construction industry. In addition to the fact that they employ natural materials, the material can simply be mixed back into the soil at the end of its life cycle. At the same time, however, one must be aware that occurrences of bentonite deposits are highly localised and are relatively limited worldwide (Reeves et al. 2006). The use of bentonite panels and bentonite-based specialised mixtures may therefore entail high transport costs. An investigation of the general suitability of different types of glacial till could mean that many construction projects in and around end moraine landscapes may be able to draw on locally occurring natural soils. A more in-depth investigation into possible methods of processing naturally occurring clays could broaden the possibilities even further.

A long-term study in Pompeii aims to address this aspect (Michette et al. 2018). A variety of different soils and mixtures from the Campania region were tested for their suitability for waterproofing measures using the series of tests described here (Breuninger 2018).



04 Installation of vertical clay barriers. (from Michette et al., 2017).

A mixture of a sandy, Vesuvian soil and a calcareous clay from the Salern Basin proved to be promising. A transdisciplinary working group will further determine the compatibility of these waterproofing methods with the archaeological building fabric. A test installation is planned in the context of a workshop on a tomb in the Porta Nocera necropolis.

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