CHARACTERIZATION OF CLASSICAL BUILDING MATERIALS USED IN 17TH CENTURY ETHIOPIAN ARCHITECTURE. APPLICATION IN THE RESTORATION OF THEIR HISTORIC AND ARTISTIC HERITAGE

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CHARACTERIZATION OF CLASSICAL BUILDING MATERIALS USED IN 17TH CENTURY ETHIOPIAN ARCHITECTURE. APPLICATION IN THE RESTORATION OF THEIR HISTORIC AND ARTISTIC HERITAGE.

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ABSTRACT

From the 15th century onwards various Jesuits missions were established in the Amhara region of Ethiopia. With the support of the local ruling class, the Jesuits constructed civil and religious buildings of great historical and artistic value according to Western standards and procedures. The restoration of this historic circuit, declared a World Heritage Site by UNESCO in 1979, will bring important benefits to the region. Various samples from each monument were taken and subjected to X-ray diffraction tests, polarized light optical microscopy, scanning electron microscopy, ultrasounds and colorimetry tests. The composition results provided important information about the provenance of the materials used by the Jesuits. Their air lime binders were also of particular interest due to the addition of locally-sourced diatomite earths to create a product with high mechanical resistance and durability. The techniques

introduced by the Jesuits can be used today in the sustainable, economical restoration of heritage in Ethiopia and adjacent regions.

KEYWORDS

Jesuit architectural heritage, Ethiopia, diatomite earths, restoration materials, lime binders, bricks, masonry stone.

1. INTRODUCTION

Today the drive towards sustainable development combines perfectly with the models for the conservation of historic heritage to create an excellent symbiosis in which to conduct field research into the restoration and characterization of materials in locations of high universal value, which require the support of different organizations, the public and private sectors and the promotion of activities and programmes at an international level.

One example is the integrated plan being carried out jointly by the UNESCO and the United Nations in the study area in Ethiopia to restore the Jesuit buildings near Lake Tana. This programme includes and interrelates culture, science and local development. It also involves the local population and tries to use best practices so as to improve among other things, the conservation of the planet, its biodiversity and environmental values. The plan also envisages restoration work in settlements of enormous heritage value, for which purpose sustainable materials and equipment will be used. When possible, the original material will be reused and existing structures will be maintained.

A non-profit organization, the World Monuments Fund (World Monuments Foundation WMF) has also been carrying out restoration work in the same area in collaboration with UNESCO (UNESCO, 2018) in an attempt to preserve sites of great architectural and historic value, via fieldwork, promotion and training.

At the same time, at a more specific local level, projects are being carried out in the important cultural tourism circuit of historic Ethiopia (Gondar, Lalibela, Aksum, etc.).

Since 2006 the University of Granada together with a multidisciplinary team from various different institutions (the Complutense University in Madrid, the Spanish Senior Research Council, the French National Centre for Scientific Research and the Institute for Sciences of Work and Business in Portugal) has been carrying out historic and archaeological research work into the monuments constructed by the Jesuits, and in particular the most important buildings situated near the city of Gondar, the capital of the Abyssinian Empire during the 17th and 18th centuries.

In 2009 funding was obtained from the AECID (Spanish Agency for International Cooperation for Development) to promote the protection of the historic cultural heritage in this region including among other buildings the Palace Complex declared a World Heritage site by UNESCO in 1979. Archaeological prospection campaigns were also carried out in 2010, 2011, 2012, 2013 and 2015, producing a wide range of research results. (Fernández et al. 2012), (Dietz et al. 2012), (Fernández 2013), (Fernández et al. 2017).

The main focus of the research was the restoration of historic buildings, which when they form part of the architectural and cultural heritage of a specific geographical area have their own unique features unlike any others, be it at a strictly conceptual, formal or composition level or from the material point of view in terms of their construction, conservation, restoration, recovery and promotion.

In the geographical area covered by the study (Ethiopia, Lake Tana area) there are a number of interesting constructions of different kinds (churches, residences, palaces for the ruling class, cisterns, fortifications etc.), of undeniable architectural worth, which are the main cultural attraction in the area. The consolidation and promotion of these monuments would lead to greater heritage and economic benefits for Ethiopia (Phillipson 1998), (Phillipson 2009).

Various analytical quantitative techniques were applied in the characterization of the mortars, concrete and renders, as used in the studies conducted by (Rosario et al. 2001), (Thorborg 2003), (Lanas 2004), (Arandigoyen and Alvarez 2007), (Acun and Arioglu 2011), (Valenca, Almeida and Julio 2012). The priority was to find materials that were compatible both with other materials and with the restoration products used to improve their performance (Luxan and Borrego 2004), (Athuman and Ngoma, 2009), Luque, Cultrone and Sebastian 2010), (Arizzi 2010), (Drdacky 2011), (Cobirzan and Balog 2013), (Hammou et al. 2013), (Torney, Forster and Szadurski 2014), (Frankeova and Slizkova (2016). It was also necessary to find out as much as possible about the process involved in the manufacture of these building materials, as this can affect the performance of the material (Margalha et al. 2011) and can help predict the type of decay it has suffered (Mosquera, Benitez and Perry 2002), (Cultrone, Sebastian and Ortega 2005), (Klisinka and Tišlova 2013).

More recently, and in a complementary way, various research works (Arandigoyen and Alvarez 2005), (Kelouaz et al 2016), (Sepulcre and Hernandez 2012), (Moropoulou et al. 2002), (Slízková, Drdácky and Viani 2015), (Thirumalini et al. 2015), (Cerezo, Mas-Barber and Kröner 2014) have been conducted in which the behaviour of additives that can improve the properties of restoration mortars has been tested. In all cases traditional materials and natural and organic resources were used, including bacteriological matter that can improve mechanical properties (European Network 2016), (BIOBRUSH 2008), (Thirumalini, Ravi and Rajesh 2017), (Jroundi et al. 2017), so obtaining savings in costs and materials.

As regards joining mortars, previous studies in other unique locations such as in (Arandigoyen and Alvarez 2007), (Moropoulou et al. 2002), (Durgesh and Dhanapala 2015), (Groot 2016), (Maurenbrecher 2008), Bianco 2013), highlight the importance of the characterization of these materials in order to ensure the right kind of restoration, the compatibility of the materials and their durability. This has helped with the characterization of the existing mortars in the masonry, ceramics and wall renders. In other cases, the study of the fundamental qualities and properties of the mortar has highlighted its importance in combating changes in temperature and humidity that cause stress at the interface and seriously damage the material, as described by (Drdáckýa and Berana 2010), (Lanas and Alvarez 2003), Lanas et al. 2004), (Moropoulou et al. 2005), (Karaveziroglou and Papayianni 1993).

The study area has a heterogeneous climate. The air temperature is not subject to extreme variations although they can be quite substantial. There are high levels of precipitation four months a year, during which the temperatures do not vary greatly. The average annual precipitation in the Lake Tana area ranges between 1140 and 1308 mm, with 115-142 days of rain. The main climate problem in this area is the combination of medium to high temperatures and high levels of moisture. Another serious problem is insolation, which is very high for eight months of the year causing huge temperature gradients in the buildings, which are subject to a great deal of heat stress (Ayalew et al. 2012), (Seleshi and Zanke 2004).

In this research the most representative materials from different constructions in the Jesuit missions in the Gondar region of Ethiopia were characterized. The study centred particularly on mortars and concretes, materials that featured widely in the form of both joining mortar and exterior render. The stones used in the masonry and the ceramic materials (bricks) used in the construction were also characterized.

These findings will enable the development of suitable conservation materials and techniques that can reduce the impact of previous restoration work for the conservation of elements of special heritage value, using locally sourced materials such as natural stone masonry, the production of air and hydraulic limes and the use of natural additives that enhance the performance of the concrete, mortars and renders used in restoration.

2. MATERIALS AND METHODS

The samples collected for analysis came from four sites, and in particular from the following buildings: Jesuit residence in Gorgora Nova (Maryam Gəmb, c. 1610), pond from the Azäzo complex (Gännätä Iyäsus, c. 1620), great Palace of Susenyos in Dänqäz (c. 1625), and the House of the Patriarch in Däbsan (Enfraz, c. 1630). Figure 1 shows the location of the missions created by the Jesuits in the Lake Tana basin, of which remains survive today.

FIGURE 1.

As can be seen in Figure 2, all the monuments, of great heritage value, are in an advanced state of decay.

FIGURE 2.

In geological terms, Ethiopia is situated in East Africa in the sector resulting from the tectonic accident that produced the Great Rift Valley, a trench running from North to South that splits the African continent in two. The continuous volcanic activity has resulted in the formation of large volcanic cones and extensive mesetas, leaving equally deep lacustrine depressions, like the depression of Lake Tana (Bergoeing 2012).

Around Lake Tana there are outcrops of materials dating from the Mid Paleocene to the sub-actual Quaternary deposits. From wall to ceiling the Ashangi formation from the Eocene is composed of an alkaline basalt with limestone intercalations; followed by the Aiba basalts dating from the Mid-Upper Oligocene, with sporadic limestone levels; moving on towards the ceiling we come to the limestone formation of Tarmaber Gussa, from the Oligocene-Miocene Age, composed of basalts, trachytes and phonolites; finally the series ends with two quaternary deposits, an older one of igneous origin, formed by a plateau of basalt and trachyte; and more recent alluvial and lacustrine deposits formed by sands, silts, clays, diatomaceous earths and limestones (Tadesse, Milesi and Deschamps 2003) (Figure 3).

FIGURE 3.

A total of 40 samples were characterized, as detailed in Table 1. The samples were classified into 5 groups corresponding to the different types of material studied (concrete masonry, mortar masonry, painted plaster, masonry stone and brick). The archaeological site and the particular building or structure from which each sample was taken are also specified.

TABLE 1.

The X-ray diffraction samples were analysed using a Bruker D8 Advance diffractometer with 2-theta geometry, using copper radiation and a Lynxeye detector, from the Scientific Instruments Centre (CIC) of the University of Granada. The composition was determined with the Xpowder software (Martin 2004), which takes into account multiple iterations of models of the mixture to ensure greater accuracy with the real diffractogram. The error is the minimum that can currently occur in XRD interpretation. According to the technical specifications of the diffractometer, it can detect minerals with a relative proportion in the sample increased to 2%.

The tests for the characterization of the mineralogy, texture and microstructure of the samples were conducted using a polarized optical microscope (Olympus BX-60) and a scanning electron microscope (SEM) Zeiss DMS 950 coupled with Microanalysis Link QX 2000.

The elastic properties (the degree of compactness) of the samples were studied using a Steinkamp BP5 ultrasonic pulse generator with 100 kHz transducers according to ASTM D 2845 (ASTM 2008), belonging to CIC-UGR.

In the samples in which this was possible, the ultrasound propagation speed (VP) was calculated in 3 directions with regard to the wall section from which the samples were taken. VP1 is the direction perpendicular to the wall, VP2 parallel to the wall and VP3 perpendicular to the other two. Total anisotropy (DM) was determined using the mathematical formulae proposed by (Guydayer 1986).

All samples were measured for colorimetric evaluation purposes. Their diffuse spectral-reflectance curves were measured in the visible range using a Konica Minolta CM-2500c Spectrophotometer, which has a wavelength of 360 nm to 740 nm and observer 2/10 degrees (CIE 1931/2, CIE 1964/10), illuminant D65, and belongs to the University of Granada (Spain).

3. RESULTS AND DISCUSSION

The XRD study of the mortar samples indicated a high presence of calcium carbonate, due to the fact that the lime binder used in the mixes sets well and has optimum carbonatation. The newly formed mineral compounds (Ca-Si) generated by the addition of diatomaceous earths could not be distinguished with XRD, due to their vitreous-amorphous nature.

XRD analysis of the masonry stone shows large amounts of Sanidine and Quartz, and very small amounts of Albite. Given that it is mainly composed of feldspar minerals it could be an igneous rock such as Trachyte, which is very common throughout the study area. The brick samples show a high presence of quartz, muscovite and calcite. The absence of new mineral phases together with the presence of calcite suggest that they were fired at a low temperature (750-850 ºC). Figure 4 includes five diffractograms, one for each of the materials studied.

FIGURE 4.

The samples studied with polarized light optical microscopy (Figure 5) reveal a high degree of compactness of the air lime mortars used in the constructions in the Lake Tana area, due to the optimum carbonatation of the Portlandite ($Ca(OH)_2$) present in the lime paste. This was undoubtedly produced by the careful process of preparing the air lime and curing it in the right conditions, out of contact with the air. The mortar binders have reaction interfaces with areas in which agglomerations of siliceous additives can be observed.

The stone sample shows a vitreous matrix with small, highly compact phenocrystals of plagioclase and pyroxene. Judging by their geological context and their characterization, the stones would appear to be from a volcanic igneous rock similar to trachyte or phonolite.

The ceramic samples included matrices based on fusible clays and tempers made out of crushed rocks or crushed ceramic products. The compactness of these materials indicates a low level of sintering and a low firing temperature. 10-20 μm pores can be observed throughout the material.

FIGURE 5. Microphotographs of mortars and stone (crossed polars).

The study of materials using SEM and their analysis with EDX (Figure 6) revealed various interesting aspects of the air lime mortars. Firstly, the fact that an extra fine siliceous additive had been added to them. The additive included above all deposits of diatom skeletons which had generated a certain degree of hydraulicity in the mixes based on air lime (portlandite). The chemical analysis (Si-Al-Ca) of the lumps in some of these samples highlighted the process of hydrolyzation and, by extension, the good compactness of the mortars and concrete, and the increase in mechanical resistance. The mortars also contain aggregates with a variable grain size from the volcanic rocks in the area (basalts, trachytes, etc.).

The ceramic products are made out of locally quarried clays and tempers. The tempers were either made out of reused crushed ceramic material or alternatively out of crushed rocks and sands of a siliceous nature. The high porosity of their components and the fact that they showed no signs of vitrification suggest that these ceramics were fired at a low temperature. The elementary analysis with EDX showed them to be similar to common pottery products. No newly formed minerals were detected that could indicate firing temperatures of over 750-850 ºC.

The EDX analysis of the masonry stones on the basis of the SEM results confirms the presence of feldspars and feldspathoids characteristic of the igneous rocks present in the geological area (trachytes and/or phonolites).

FIGURE 6.

As regards the ultrasound measurements, Table 2 includes the average values for the mortars, stones and bricks collected at different locations, with average speed and standard deviation data.

TABLE 2. Ultrasound pulse transmission speeds for samples of joining mortar, rendering mortar, masonry stones and bricks.

All the materials obtained expected values, highlighting in particular the natural stone materials (see Figure 7). These masonry pieces come from massive, scarcely porous rocks which have high ultrasonic pulse transmission speed values, so guaranteeing their durability in buildings. The mortars, concrete and renders made with air lime obtained either expected values or in some cases slightly higher values than previous measurements for other air lime mortars (Arizzi et al 2015). This would suggest that the increase in transmission speed, the reduction in porosity and the increased compactness are due to the incorporation of siliceous additives (diatomaceous earths). The ceramic materials show similar values to those for the group of common pottery, with very low firing temperatures that were incapable of causing sintering or initial signs of vitrification in the materials with plastic properties (Cultrone et al 2004).

FIGURE 7.

As regards the structural anisotropy (DM), this ranges between 1.00 % in the case of masonry concrete and 5.00 % for stone, revealing only minimal differences. This indicates that the samples behave in a homogeneous way and anisotropy cannot be considered a factor as far as reducing resistance is concerned.

Analysis of the colour of the mortar samples (see Figure 8) revealed a yellow tone with low saturation, medium to high lightness and a whitish grey visual appearance, characteristic of mortars, concrete or waterproof renders made with air lime binders. The stone is very dark and relatively unsaturated, which means that its green shade does not stand out due to the lack of lightness. It has the same visual appearance as the rocks (basalts and trachytes) from the Lake Tana area. The ceramic materials have yellow red tones, are relatively unsaturated and have low lightness. This suggests a low firing temperature with partially reducing firings, as often found in low quality ceramics. Table 3 sets out the colorimetric values corresponding to the different groups of samples studied.

FIGURE 8.

TABLE 3.

The results obtained after carrying out the different characterization techniques offered us a very approximate vision of the physical and mechanical properties of the construction materials used in the Jesuit buildings at the Gorgora Nova, Danqaz, Azazo and Dabsan sites, and of their conservation and durability conditions. Their suitability was also checked by comparing them with the results from a range of publications. The colour characterization was useful for two reasons in that it enabled the updated classification of the artificial materials studied and the creation of a colour chart for restoration works.

In the same way and after characterizing the mineral composition of the samples from some of the most important constructions, this research also confirmed that the production and use of air lime enhanced with siliceous additives was a technical breakthrough introduced into this area by the Jesuit missionaries in the 17th century. This suggests that they had an excellent knowledge of construction techniques, perhaps acquired from classical sources, and were prepared to use a selection of local raw materials in the actual building works. The incorporation of diatomaceous earths was clearly a deliberate step to improve the mechanical resistance of the mortars, concrete and renders. Their waterproofing was also improved through the reaction of the Portlandite with the amorphous silica in the opaline diatom shells to form hydrolyzable compounds of Ca-Si composition. This suggests that the diatomaceous earths were deliberately added to the lime paste as no heat-related alteration could be observed in the frustules of the binder mixes. This increased both mechanical resistance and waterproofing.

The decision to use igneous stones in the construction of the buildings as compared to other kinds of sedimentary stones was a question of maximization of resources. In this area there was an abundance of fragmented trachytes and basalts, the main raw materials used to build the masonry walls, as compared to the use of other less local materials in the Lake Tana area.

The ceramic materials were also made of local raw materials. Although the clay deposits in the area are of a low ceramic quality (micaceous), they can be used to make ceramics with an acceptable degree of compactness at low firing temperatures. The generally low firing temperatures and the low compositional refractoriness have produced ceramic materials with high porosity and little or no sintering. Although the Jesuits used bricks in some of the buildings, their main building material was the highly resistant siliceous stone available in abundant quantities in this area. The research also indicates that the Jesuits decided that the local binding materials required technical improvements (artificial binders).

4. CONCLUSIONS

The recovery and promotion of the architectural cultural heritage in different kinds of buildings (and other structures) in varying locations poses a real challenge for research in the field of building materials and in conservation practice. The composition of the materials, the way they are laid in the building and their state of decay and deterioration are key aspects in the necessary analysis that must be carried out prior to making any proposals regarding restoration work.

Locally-sourced materials can be used in restoration work today, following the procedures used by the Jesuits in the 17th century. The limestones can be used to make the air binders in the restoration of the buildings and the walls and for producing inorganic consolidants based on limewater $Ca(OH)_2$ suspensions, which allow the original renders and mortars to harden. The inclusion of diatomites after the slaking of the lime will help increase the mechanical resistance of the mortars after the restoration work.

It is important to make clear that the use of siliceous additives has been a constant continual practice ever since classical antiquity, as can be seen in the development of Roman cement made with air lime and the addition of “lapilli” or volcanic ash with a high silica content. This practice, as well as their knowledge of the correct way to prepare and preserve air lime, shows that the Jesuits who moved to Abyssinia had an in-depth understanding of building materials, probably based on ancient treatises such as *De architectura* by Vitruvius (Vitrubio de Architectura 1997). It is very important that the siliceous additive used in binders based on air lime is of high quality, due to its chemical nature (Si), which implies good reactivity between the additive and lime matrix, its morphology (shells with micro-orifices) and its small size (large specific surface area).

The ceramic materials, above all large bricks, were not widely used in the Jesuit buildings. In general, they are poor quality and have insufficient mechanical resistance, unlike the stone used in the masonry. This stone is widely available in the area, extremely durable and highly compatible with the original mortars and concretes. The use of bricks of this kind in conservation and restoration work would not therefore be suitable. Instead locally quarried stone should be used intensively, as it is easily available and very durable.

The analytical techniques are ideal for the characterization of the building materials and for assessing their technical condition and the alterations they have undergone. They can also be used for making conservation and restoration proposals. One of the most important techniques was the colorimetry study of the different samples, which will facilitate good restoration work by ensuring that the appropriate restoration materials are selected and that these materials match adjacent existing materials.

Finally, it is important to emphasise that the Jesuits were a source of knowledge in the different countries that they visited and settled, often creating new building materials on the basis of their experience and knowledge of historic sources. This made it easier for them to access different cultures such as the inward-looking Abyssinian society of the 16th and 17th century. The Jesuits shared and spread their knowledge in truly exceptional settings, so giving rise to the fascinating buildings constructed in the Lake Tana area of Ethiopia.

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6. BIBLIOGRAPHY

Acun, S., Arıoglu, N. 2011. The evaluation of lime mortars and plasters with the purpose of conservation and restoration. Comission VI,WG VI/6.

Arandigoyen, M., Alvarez, J.I. 2007. Pore structure and mechanical properties of cement-lime mortars. *Cement and Concrete Research* 37 (5):767-775. https://doi.org/10.1016/j.cemconres.2007.02.023

Arizzi, A. 2010. Characterization of Lime Mortars for their use in Restoration of Cultural Heritage and in Modern Construction. *Revista de la sociedad española de mineralogía.* Macla 12. septiembre. 78-79.

Arizzi, A., Martinez-Huerga, G., Sebastián-Pardo, E., Cultrone, G. 2015. Mineralogical, textural and physical-mechanical study of hydraulic lime mortars cured under different moisture conditions. *Materiales de Construcción* 65 (318), April–June, e053. ISSN-L: 0465-2746. doi: http://dx.doi.org/10.3989/mc.2015.03514

ASTM D 2845. 2008 Standard Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock. American Society for Testing and Materials. Ed. ASTM. 7 p.

Athuman, M., Ngoma, K. 2009. Characterization and consolidation of historical lime mortars in cultural heritage buildings and associated structures in East Africa. University of Dar-es-Salaam. PhD. TRIKA-BKN, Bulletin 101. ISSN 1103-4270.

Ayalew, D., Tesfaye, K., Mamo, G., Yitaferu, B., Bayu, W. 2012. Variability of rainfall and its current trend in Amhara Region, Ethiopia. *African Journal of Agricultural Research* 7(10): 1475-1486, 12. https://doi.org/10.5897/AJAR11.698

Bergoeing, J.P. 2012. Tectónica de placas y vulcanismo en el área del gran Rift. Mercator – *Revista de Geografía da UFC*, 11 (26): 183-216. Universidad Federal do Ceará, Fortaleza, Brasil.

Bianco, N., Calia, A., Denotarpietro, G., Negro, P. 2013. Hydraulic mortar and problems related to the suitability for restoration. Periodico di Mineralogia *International Journal of mineralogy, crystallography, geochemistry, ore deposits, petrology, volcanology,* 82 (39): 529-542. DOI: 10.2451/2013PM0031

BIOBRUSH Result In Brief. Project reference: EVK4-CT-2001-00055. Funded under: FP5-EESD (2008). Permalink: http://cordis.europa.eu/result/rcn/84151_en.html

Cerezo, A., Mas-Barber, X., Kröner, S. 2014. Study of the mechanical properties of mortars based on organic binders used in the reproduction of outdoor artworks. CeROArt. Conservation, exposition, restauration d'Objects d'Art. Teaching Conservation-Restoration. European Network for Conservation-Restoration -Symposium 26th March 2014- Edited by Wolfgang Baatz.

Cobirzan, N., Balog, A-A. 2013. Characterisation of mortars compatibility using microscopical and XRD analysis. Atomic and nuclear physics. *Romanian Journal of Physics*, Vol. 59, Nos. 3–4: 265–271.

Cultrone, G., Sebastian, E., Elert, E., De la Torre, M.J., Cazalla, O., Rodriguez–Navarro, C. 2004. Influence of mineralogy and firing temperature on the porosity of bricks. *Journal of the European Ceramic Society* 24: 547–564 https://doi.org/10.1016/S0955-2219(03)00249-8

Cultrone, G., Sebastián, E., Ortega Huertas, M. 2005. Forced and natural carbonation of lime-based mortars with and without additives: Mineralogical and textural changes. *Cement and Concrete Research* 35: 2278–2289.

De Luxan, M.P., Borrego, F. 2004. Characterization and selection of mortars in the restoration of the kings portal (Benavente, Zamora). *Materiales de Construcción* 54, nº 273: 35-44.

Dietz, C., Catanzariti, G., De la Presa, P., Fernández Martínez, V. 2012. 3D documentation using laser scanning of remains of the Jesuit Mission (1624-31) in the region of Lake Tana (Ethiopia). *e-conservation magazine*. 24. 106.

Drdacky, M. 2011. Non-standard Testing of mechanical characteristics of historic mortars. *International Journal of Architectural Heritage* 5: 383-394.

Drdáckýa, M., Berana, P. 2010. Compatible Dilation Limits of Masonry Joint Mortars. *International Journal of Architectural Heritage: Conservation, Analysis, and Restoration* 4 (2): 155-176. Special Issue: Select Papers from HMC 2008 – The First Historical Mortars Conference. DOI: 10.1080/15583050902914686

Durgesh, C., Rai, S. Dhanapala. 2015. Mineralogical and Mechanical Properties of Masonry and Mortars of the Lucknow Monuments Circa the 18th Century. *International Journal of Architectural Heritage: Conservation, Analysis, and Restoration* 9 (3): 300-309.

European Network for Conservation-Restoration. 2016. Symposium 15-16 April.. Edited by Rupert Featherstone and Nico Broers

Fernández Martínez, V. 2013. Enlivening the dying ruins: history and archaeology of the Jesuit Missions in Ethiopia, 1557–1632. *Culture & History Digital Journal* 2(2): e024. doi: http://dx.doi.org/10.3989/chdj.2013.024

Fernández Martínez, V., De Torres, J., Martínez d'Alòs-Moner, A., Cañete, C. 2017. *The archaeology of the Jesuit Missions in Ethiopia (1557-1632).* Jesuit Studies. Modernity through the prism of Jesuit History. Vol. 10.Ed. Brill, Leiden/Boston. ISBN. 978-90-04-32469-5

Fernández Martínez, V., Martínez D'Alos-Moner, A., De Torres, J., Cañete, C., 2012. Archaeology of the Jesuit Missions in the Lake Tana Region. *Aethiopica* 15 (2012), 72–91. ISSN: 2194–4024

Frankeová, D., Slízkova, Z. 2016. Determination of the pozzolanic activity of mortar's components by thermal analisys. *Journal of thermal analisys and calorimetry* 125 (3): 1-9.

Groot, C. 2016. Repair mortars for historic masonry; Effects of the binder choice on durability. *HERON* 61 (1): 33-56.

Guydader, J., Denis, A. 1986. Propagation des ondes dans les roches anisotropes sous contrainte e´valuation de la qualite´ des schistes ardoisiers, *Bulletin of Engineering Geology* 33 (1986) 49e55.

Hammou, Y., Fihri fassi, H., Van parys L., Bideq. Descamps, M., Tironi, S., Lamant, N. 2013. Study of mechanical compatibility at the mortar-block interface in a heritage building. 21[ème] Congrès Français de Mécanique. Bordeaux, 26 au 30 août.

ISO 11664-1:2007. ISO 11664-2:2007. ISO 11664-4:2008.

Jroundi, F., Schiro, M., Ruiz-Agudo, E., Elert, K., Martín-Sánchez, I., González-Muñoz, M.T., Rodriguez-Navarro, C. 2017. Protection and consolidation of stone heritage by self-inoculation with indigenous carbonatogenic bacterial communities. *Nature Communications* 8, Article number: 279. https://doi:10.1038/s41467-017-00372-3

Karaveziroglou, M., Papayianni, I. 1993. Compressive strength of masonry with thick mortar joints. Conservation of stone and other materials. Vol. one: causes of disorders and diagnosis. Vol. two: prevention and treatments. Proceedings of the international RILEM/UNESCO congress. Paris, June 29-July 1. 212-219.

Kelouaz, K, Guebboub Lakhdar, S., Deloum, S., Hamiene, M. 2016. Mortar of lime and natural cement for the restoration of built cultural heritage. *International Journal of Engineering Research & Science* (IJOER) ISSN [2395-6992]. Vol-2, Issue-1.

Klisińska-Kopacz, A., Tišlova, R. 2013. The Effect of Composition of Roman Cement Repair Mortars on Their Salt Crystallization Resistance and Adhesion. *Procedia Engineering* 57: 565 – 571.

Lanas, J., Alvarez, J.I. 2003. Masonry repair lime-based mortars: Factors affecting the mechanical behaviour. *Cement and Concrete Research* 33: 1867-1876.

Lanas, J., Pérez Bernal, J.L., Bello, M.A., Alvarez Galindo, J.I. 2004. Mechanical properties of natural hydraulic lime-based mortars, *Cement and Concrete. Research* 34: 2191-2201. https://doi.org/10.1016/j.cemconres.2004.02.005

Luque, A., Cultrone, G., Sebastián, E. 2010. The Use of Lime Mortars in Restoration Work on Architectural Heritage. *Materials, Technologies and Practice in Historic Heritage Structures. Book Part. Part III*. 197-207. DOI 10.1007/978-90-481-2684-2_11

Margalha, G., Veiga, R., Santos Silva, A.; De Brito, J. 2011. Traditional methods of mortar preparation: the hot lime mix method. *Cement and concrete composites* 33: 796-804. 10.1016/J.CEMCONCOMP.2011.05.008

Martín Ramos, J.D. 2004. XPowder, a software package for powder X-ray diffraction analysis. Legal Deposit GR 1001/04. Spain.

Maurenbrecher, A.H.P., Trischuk, K., Rousseau, M.Z., Subercaseaux, M.I. 2008. Repointing Mortars for Older Masonry Buildings–Design Considerations. *Construction Technology* Update No. 67. National Research Council of Canada March. ISSN 1206-1220.

Moropoulou, A., Bakolas, A., Moundoulas, P., Aggelakopoulou, E., Anagnostopoulou, S. 2005. Strength development and lime reaction in mortars for repairing historic masonries. *Cement and Concrete Research,* 27: 289-294.

Moropoulou, M., Bakolas A., Moundoulas, P., Aggelakopoulou, E., Anagnostopoulou, S. 2002. Design and evaluation of restoration mortars for historic masonry using traditional materials and production techniques. MRS Proceedings Volume 712/2002 DOI: http://dx.doi.org/10.1557/PROC-712-II2.7

Mosquera, M.J., Benitez, D., Perry, S.H.. 2002. Pore structure in mortars applied on restoration: Effects on properties relevant to decay of granite buildings, *Cement and Concrete. Research* 32: 1883-1888.
Phillipson, D.W. 1998. *Ancient Ethiopia: Aksum, its antecedents and successors.* London: British Museum Press.

Phillipson, D.W. 2009. The first millennium BC in the highlands of northern Ethiopia and South-central Eritrea: a reassessment of cultural and political development. *African Archaeological Review* 26: 257-74

Rosário Veiga, M., Aguiar, J., Santos Silva A., Carvalho, F. 2001. *Methodologies for characterisation and repair of mortars of ancient buildings. Historical Constructions*, P.B. Lourenço, P. Roca (Eds.), Guimarães.

Seleshi, Y., Zanke, U. 2004. Recent changes in rainfall and rainy days in Ethiopia. International Journal Climatology 24: 973–983. https://doi.org/doi:10.1002/joc.1052

Sepulcre Aguilar, A., Hernández-Olivares, F. 2012. Interfacial Transition Zone (ITZ) Analysis in Hydraulic Lime Restoration Mortars for Grouting of Historical Masonries. *International Journal of Architectural Heritage: Conservation, Analysis, and Restoration*, 6 (4): 396-414.

Slíz˘ková, Z., ˇ Drdácky´, M., Viani, A. 2015. Consolidation of weak lime mortars by means of saturated solution of calcium hydroxide or barium hydroxide. *Journal of Cultural Heritage* 16: 452–460. http://dx.doi.org/10.1016/j.culher.2014.09.003

Tadesse, S., Milesi, J-P., Deschamps 2003. Geology and mineral potential of Ethiopia: a note on geology and mineral map of Ethiopia. *Journal of African Earth Sciences.* 36 (4): 273-313. https://doi.org/10.1016/S0899-5362(03)00048-4

Thirumalini, S., Ravi, R., Rajesh, M. 2017. Experimental investigation on physical and mechanical properties of lime mortar: Effect of organic addition. *Journal of Cultural Heritage*. In Press, Corrected Proof. https://doi.org/10.1016/j.culher.2017.10.009

Thirumalini, S., Sekar, S.K., Bhuvaneshwari, B., Nagesh R. Iyer. 2015. Bio-inorganic composites as repair mortar for heritage structures. *Journal of Structural Engineering* 42 (4): 294-304.

Thorborg von Konow. 2003. EUROMAT, Symposium P2- *Material and conservation of Cultural Heritage*, EPFL- Lausanne.

Torney, C., Forster, A.M., Szadurski, E.M. 2014. Specialist 'restoration mortars' for stone elements: a comparison of the physical properties of two stone repair materials. *Heritage Science* 2:1.
UNESCO http://whc.unesco.org/fr/actualites/1136/ (accessed December 10, 2017).

Valença, J. Almeida, C. Júlio, E.S. 2012. Concrete heritage: Tentative guidelines for the 'Patch Restoration Method'. *Concrete Repair, Rehabilitation and Retrofi tting III* – Alexander et al. (eds) 2012 Taylor & Francis Group, London, ISBN 978-0-415-89952-9.

Vitrubio. *Los 10 libros de Architectura*. Primera edición en «Alianza Forma»: 1995 Primera reimpresión en «Alianza Forma»: 1997. Ed. cast.: Alianza Editorial, S. A., Madrid.

Whitney, D.L., Evans, B.W. 2010. Abbreviations for names of rock-forming minerals. *American Mineralogist.* 95: 185–187. 0003-004X/10/0001–185$05.00/DOI: 10.2138/am.2010.3371 185
World Monuments Fund (WMF). http://whc.unesco.org/es/actividades/156/ (accessed December 10, 2017).

FIGURE CAPTIONS

FIGURE 1. Left, geographic location of Lake Tana and the Amhara region within Ethiopia. Right, geographic location of the four archaeological sites and former Jesuit missions where the samples were taken. Two cities existing today (Gondar and Bahir-Dar) are also indicated.

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FIGURE 5. Microphotographs of mortars and stone (crossed polars).

Microphotographs taken with polarized light optical microscopy and scanning electron microscopy (SEM). A. Lime mortar from the cistern at the Gorgora Nova historic site (GOR-7), 20x, crossed nicols. Detail of the concentration of additives made with diatomaceous earths in a lime matrix (edges marked with white arrows and red lines). B. Massive aspect of the lime mortar from the pond at Azazo (ASZ-7), 20x, crossed nicols, with structures that indicate the presence of siliceous additives and recrystallizations of secondary calcite in the pores. C-D. Ceramic material from Dabsan (DAB-11), 40x, crossed nicols, with detail of the matrix and pores, and of fine tempers. This includes crushed ceramic material and temper. E-F. Lime mortar from the Palace at Dangaz (DAN-6), 20x, crossed nicols. The siliceous additives made from diatoms are highlighted. G. Lime mortar from Gorgora Nova (GOR-4) 20x, crossed nicols. The presence of siliceous additives is marked in red. H. Masonry stone from the Dabsan site (DAB-10), 20x, crossed nicols (triangle). Plagioclases in a vitreous matrix, (rhombus). Pyroxene in a vitreous matrix of trachyte.

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temperature from the Dabsan (DAB-11) site, with high porosity and negligible fusion between the particles. The EDX analysis showed that its composition was typical of a common pottery product. H. SEM image of masonry stone from the Dabsan archaeological site (DAB-10). Detail of the plagioclase in the trachyte and its EDX analysis.

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TABLE 1. List of samples studied during this research. The location and the type of material are also specified.

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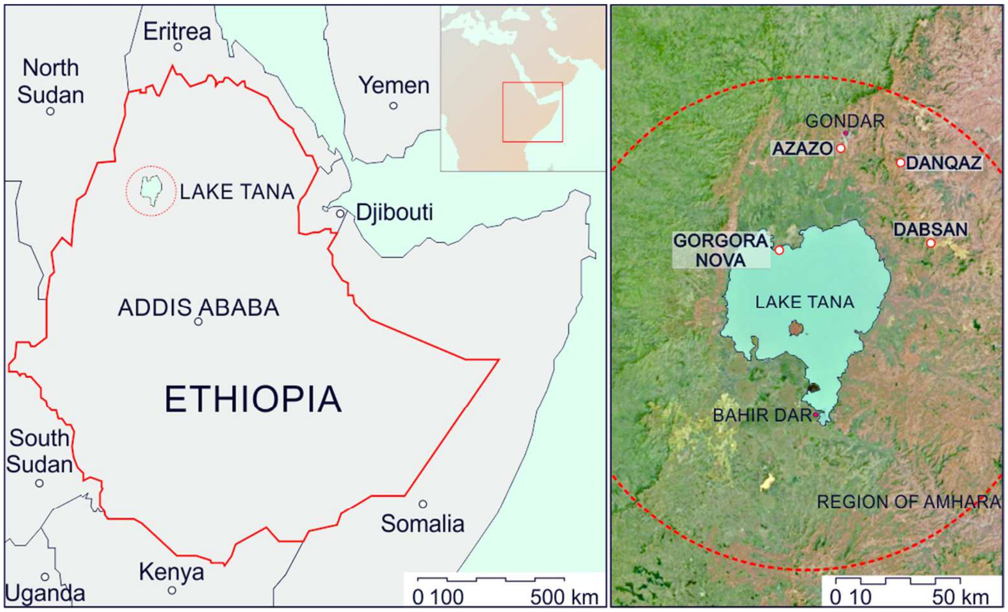
		GORGORA NOVA	**AZAZO**	**DANQAZ**	**DABSAN**
CONCRETE MASONRY	POND (WALLS)		AZO-1 AZO-2 AZO-3 AZO-4		
	CHURCH			DAN-1 DAN-2	
	WALL PILASTER	GOR-4 GOR-5			
	WALLS				DAB-1 DAB-2 DAB-3 DAB-4
MORTAR MASONRY	POND (FOUNDATION)		AZO-5 AZO-6 AZO-7 AZO-8 AZO-9 AZO-10		
	PALACE			DAN-3 DAN-4	
	UNDERGROUND WATER DEPOSIT	GOR-6 GOR-7		DAN-7 DAN-8	DAB-5 DAB-6 DAB-7
PAINTED PLASTER	DOGS AREA OF PALACE			DAN-5 DAN-6	
MASONRY STONE	LINTELS	GOR-1 GOR-2 GOR-3		DAN-1 DAN-2	
	WALLS				DAB-8 DAB-9
	VOUSSOIRS AND JAMBS IN DOORS AND WINDOWS				DAB-10
BRICK	VOUSSOIRS AND JAMBS IN DOORS AND WINDOWS		AZO-11	DAN-7	DAB-11

TABLE 2. Ultrasound pulse transmission speeds for samples of joining mortar, rendering mortar, masonry stones and bricks.

		Masonry concrete			Masonry mortar			Painted plaster			Masonry brick			Masonry Stone		
Site	m/s	V_{p1}	V_{p2}	V_{p3}	V_{p1}	V_{p2}	V_{p3}	V_{p1}	V_{p2}	V_{p3}	V_{p1}	V_{p2}	V_{p3}	V_{p1}	V_{p2}	V_{p3}
Azezo	□	2185	2151	2075	2288	2260	2264				1320	1456	1345	4854	4521	4715
	σ	90	91	85	76	84	102				84	82	89	83	83	83
Danqaz	□	1984	2002	2000	2304	2276	2280	2355			1444	1584	1280	4808	4475	4669
	σ	70	71	70	69	77	92	68			91	89	97	83	83	83
Gorgora Nova	□	2285	2251	2175	2225	2299	2219				1494	1601	1274	4887	4554	4748
	σ	90	86	84	75	84	84				82	79	89	96	96	96
Dabsan	□	2302	2288	2282	2221	2295	2214				1325	1597	1565	4856	4523	4717
	σ	75	78	79	76	84	93				93	94	79	83	83	83

TABLE 3. Colorimetric values according to the system (ISO 11664 2007) for samples of joining mortar, render mortar, decoration, concrete mortar, render and masonry stones.

		Masonry mortar					Painted mortar rendering					Masonry concrete					Rendered mortar					Masonry stone				
Site-values		L*	a*	b*	C	h_{ab}	L*	a*	b*	C	h_{ab}	L*	a*	b*	C	h_{ab}	L*	a*	b*	C	h_{ab}	L*	a*	b*	C	h_{ab}
Azezo	□	69,7	5,2	14,1	15,0	69,7						63,9	4,2	15,3	15,9	74,6	56,5	5,9	15,5	16,5	69,2	26,0	-5,0	2,0	5,4	-21,7
	σ	4,2	0,7	1,1	1,0	1,2						4,1	0,8	0,9	0,9	0,9	2,3	0,3	0,4	0,4	0,9	0,9	0,3	0,6	0,2	3,0
Danqaz	□	66,7	5,1	15,3	16,1	71,6	60,7	6,1	16,5	17,6	69,6	63,2	4,3	14,9	15,5	73,6	57,3	5,2	16,0	16,8	72,0	26,9	-5,0	1,6	5,2	-17,8
	σ	4,1	0,8	0,9	0,9	0,9	5,1	0,4	0,7	0,7	0,6	6,7	0,8	3,2	3,3	0,7	2,7	0,6	0,3	0,3	0,9	0,9	0,3	0,5	0,3	3,2
Gorgora Nova	□	70,4	4,8	14,8	15,5	72,3						63,9	4,0	15,0	15,5	75,0	58,2	5,0	15,8	16,6	72,4	26,4	-4,8	1,6	5,0	-18,1
	σ	3,5	0,6	0,9	1,0	1,3						4,2	0,8	1,0	0,9	0,9	4,3	0,8	0,9	0,9	0,9	0,5	0,3	0,4	0,4	3,6
Dabsan	□	57,7	6,1	15,5	16,7	68,7						64,1	4,8	15,0	15,8	72,3	57,1	5,0	15,9	16,7	72,6	26,0	-5,0	1,5	5,2	-16,6
	σ	0,5	0,2	0,4	0,4	0,4						5,4	0,7	3,0	3,1	0,9	5,1	1,2	1,0	1,0	0,9	0,5	0,3	0,5	0,3	3,1



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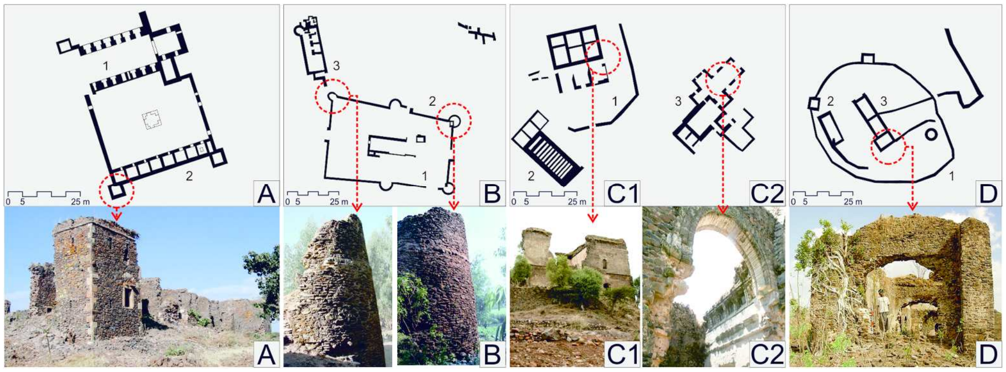
97x58mm (300 x 300 DPI)



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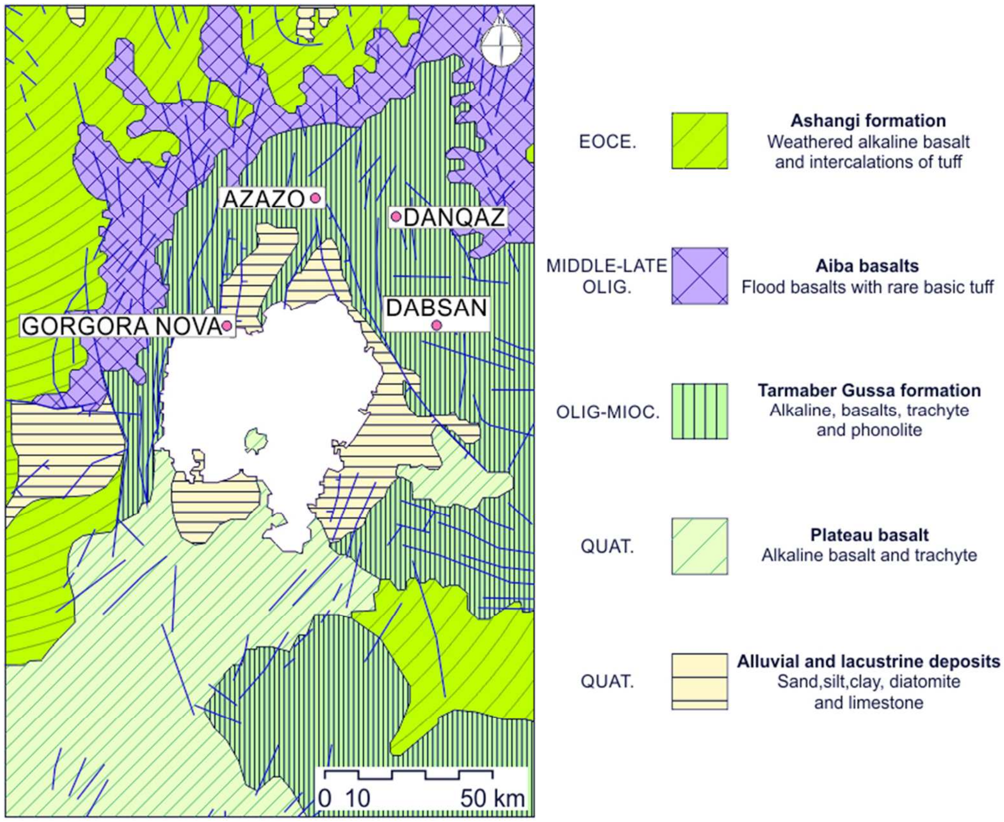
188x68mm (300 x 300 DPI)



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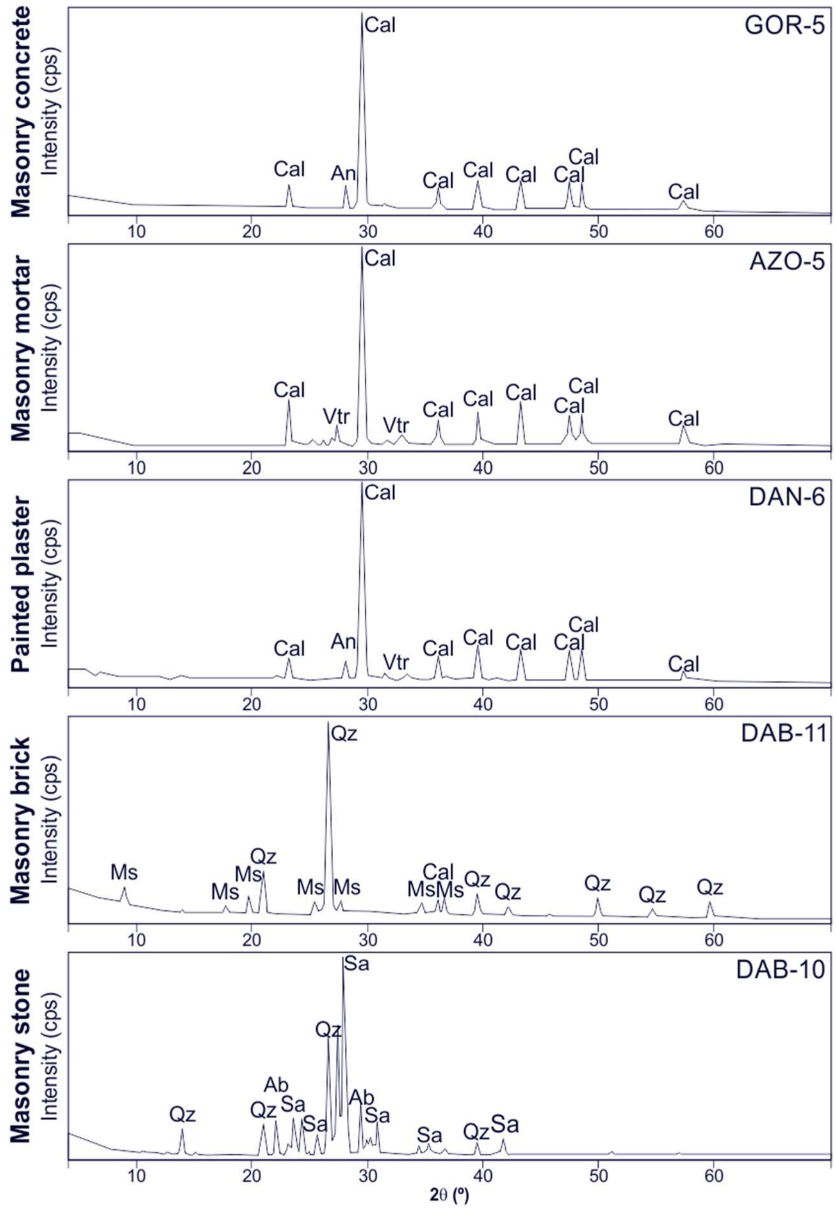
72x59mm (300 x 300 DPI)



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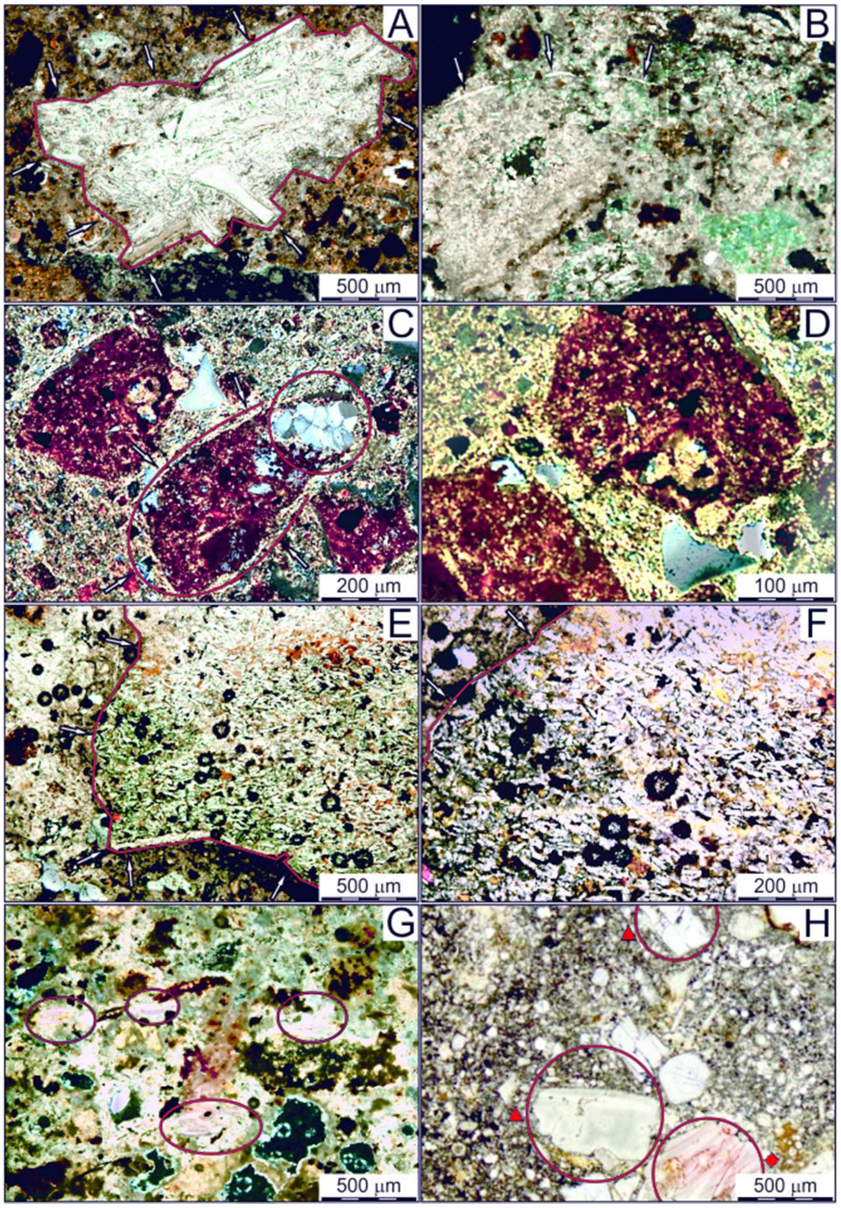
70x102mm (300 x 300 DPI)



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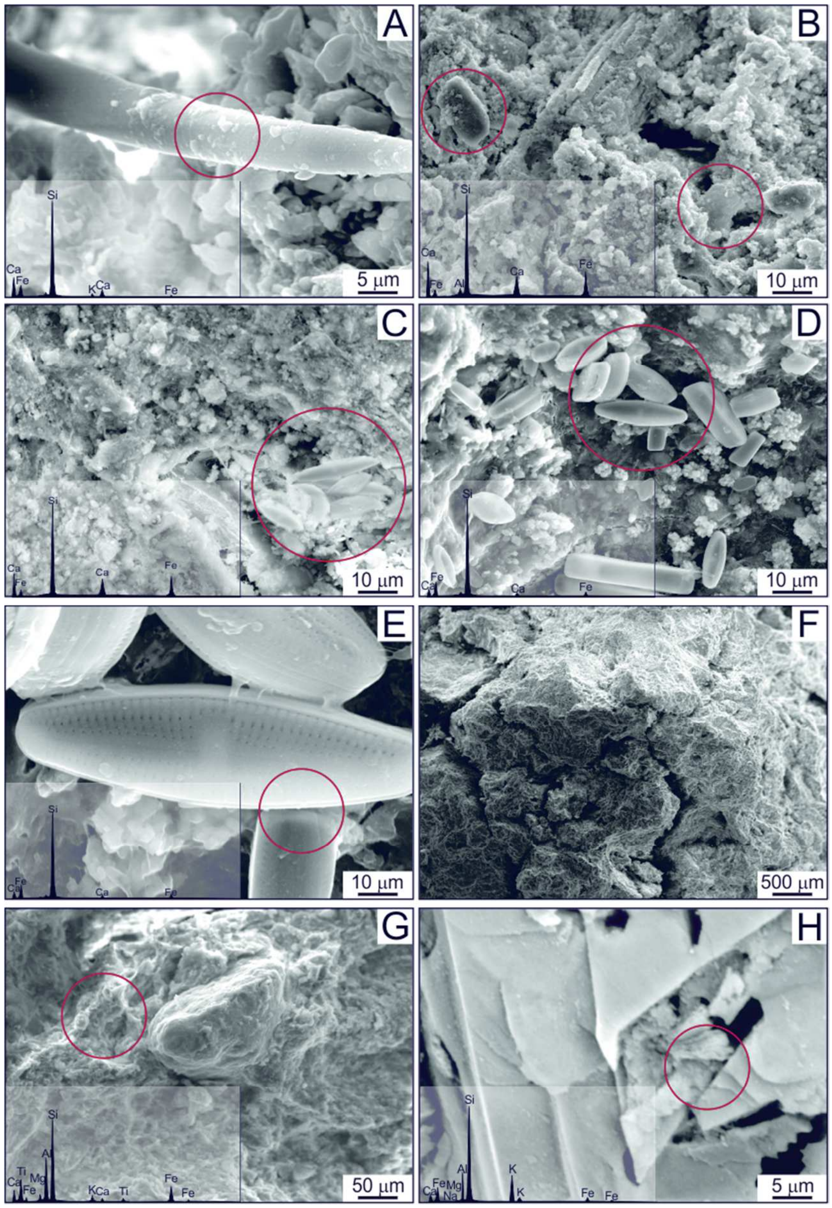
56x80mm (300 x 300 DPI)



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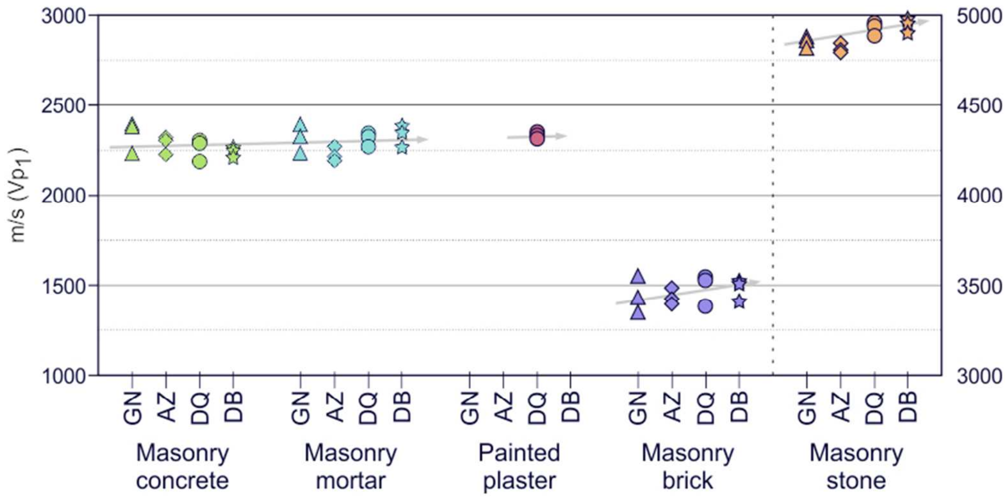

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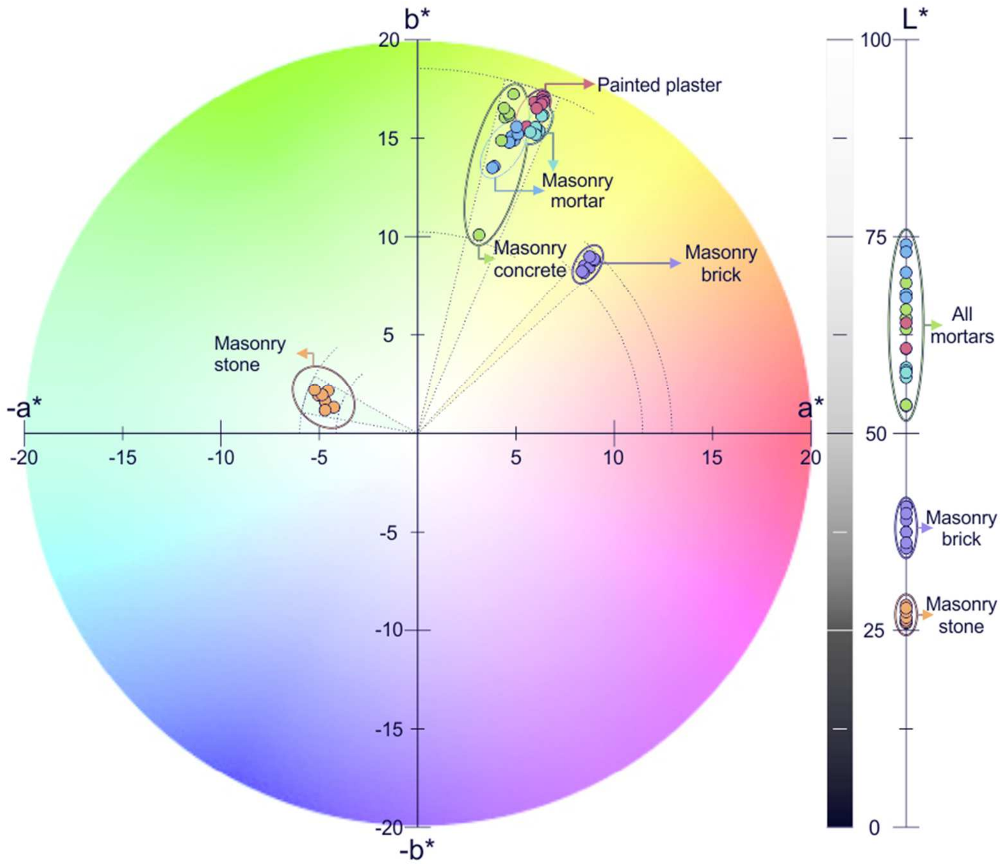
70x34mm (300 x 300 DPI)



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76x65mm (300 x 300 DPI)