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CLASSIFICATION OF BUILDING STONES OF THE FRANGOKASTELLO CASTLE, SFAKIA, CRETE

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Abstract

Frangokastello is a medieval castle which was built by the Venetians in 1371-74 in a narrow coastal zone at the southeastern part of the White Mountains, approximately 12 km east of Chora Sfakion. The region around Frangokastello characterized by a strong morphological relief, which was formed by activity of normal faults striking E-W, NNE-SSW and NNW-SSE. The region of interest has covered at the surface from sequences mainly marine sediments of Tortonian, Low Pliocene and Lower Pleistocene.

From the Middle Pleistocene multiple alluvial fans have been cover the alpine basement of the region which consists from metamorphic rocks of the Plattenkalk Group, Trypali Unit and Phyllite Quartzite Series as well the youngest in age formations. Rounded and angular fragments of rock materials from alpine and post alpine formations transported and deposited within the various parts of alluvial fan which had deposited over the Frangokastello formation, constituted the building stones for the construction of the castle. The microclimate of the region and the intense tectonic activity associated with relatively high rates of uplift of the tectonic segments in the region, has critically affect not only the static of the castle but also the resistance from the weathering of building stones after physical dismantling large parts of the binding cement and surface from outer wall. On the basis of the above, the objective of this work is initially the collection of bibliographic data related to the stratigraphy and tectonics of the region. The results obtained, combined with the results from counting and statistical processing of various lithological types of building materials of the castle can be considered input data to form static models, in the framework of proposals for maintenance and restoration of the monument.

Keywords: *Alluvial fan, building materials, restoration, monument.*

Περίληψη

Το Φραγκοκάστελλο είναι μεσαιωνικό κάστρο που χτίστηκε στο διάστημα 1371-74 από τους Βενετούς σε μια στενή παράκτια ζώνη στο νοτιοανατολικό τμήμα των Λευκών Όρεων, περίπου 12 χιλιόμετρα ανατολικά της Χώρας Σφακίων. Αυτό το τμήμα χαρακτηρίζεται από ένα έντονο μορφολογικό ανάγλυφο που η δημιουργία του καθορίστηκε από την κινητικότητα κανονικών ρηγμάτων με γενικές διευθύνσεις Α-Δ, ΒΒΑ-ΝΝΔ και ΒΒΔ-ΝΝΑ. Την περιοχή ενδιαφέροντος δομούν επιφανειακά ακολουθίες (κυρίως θαλάσσιες) του Τορτονίου, του Κάτω Πλειοκαίνου και του Κατώτερου Πλειστόκαινου. Από το Μέσο Πλειστόκαινο πολλαπλές συμφύσεις αλλουβιακών ριπιδίων

κάλυψαν τόσο το αλπικό υπόβαθρο της ευρύτερης περιοχής που αποτελείται από τα μεταμορφωμένα πετρώματα της Ομάδας των Πλακωδών Ασβεστολίθων, της ενότητας Τρυπαλίου και της Φυλλιτικής Χαλαζιακής Σειράς καθώς και τους νεότερους σε ηλικία σχηματισμούς. Στρογγυλωμένα και γωνιώδη κλάσματα πετρωμάτων των αλπικών αλλά και μεταλπικών σχηματισμών που μεταφέρθηκαν και αποτέθηκαν εντός των διαφόρων τμημάτων των αλλουβιακών ριπιδίων αποτέλεσαν τους δομικούς λίθους για της κατασκευή του κάστρου. Το μικροκλίμα της περιοχής και η έντονη τεκτονική δραστηριότητα που σχετίζεται με σχετικά υψηλούς ρυθμούς ανύψωσης των ρηξιτεμαχών στην περιοχή, επηρέασαν καθοριστικά όχι μόνο την στατική του κάστρου αλλά και την αντοχή στην αποσάθρωση των δομικών του λίθων μετά την φυσική αποψίλωση μεγάλων τμημάτων του κονιάματος του εξωτερικού της τοιχοποιίας.
Με βάση τα ανωτέρω στόχος της εργασίας αυτής αποτέλεσε αρχικά η συλλογή βιβλιογραφικών δεδομένων σχετικών με την στρωματογραφία και τεκτονική της περιοχής. Τα αποτελέσματα που προέκυψαν συνδυαζόμενα με τα αποτελέσματα από την καταμέτρηση και στατιστική επεξεργασία των διαφόρων λιθολογικών τύπων των δομικών υλικών του κάστρου μπορούν να αποτελέσουν δεδομένα εισαγωγής μοντέλων στατικότητας, στα πλαίσια των προτάσεων συντήρησης και αποκατάστασης του μνημείου.
Λέξεις κλειδιά: Αλλουβιακά *ριπίδια, δομικά υλικά, συντήρηση, μνημείο.*

1. Introduction

The Venetian castle of Frangokastello is built in 1371-1374 in Sfakia region, a narrow coastal zone in the south-eastern part of the White Mountains and was the basis of a Venetian military force, which essentially never settled in the castle. There have been many alterations to the Frangokastello, particularly in the period 1866-1869 by Mustafa Naili; however in its current shape does not show significant differences compared with the representations of the Venetian drawings. In this sense it follows the old fortification perceptions, before the prevalence of "bastion system", which will arrive in Crete before the mid-16th century. The castle is a rectangular building with vertical walls and four-sided towers at four corners, from which the southwest is much higher. The towers and the walls have on their edges jagged battlements. The main entrance was located south and its current form is a reconstruction of the 19th century. Another entrance has been opened in the east.

The three small towers are preserved with several phases of reconstruction, mainly on floors. From the preserved old evidence suggests that the ground floor was vaulted and the upper part rebuilt many times with mezzanine and gravel roof on the first floor. The largest tower maintained by smaller operations. This tower was a special defensive element of the fort, as was able to accommodate larger number of combatants and because of its location there was a greater visibility.

The ground-floor buildings held in the inner courtyard are reconstructed on recently on the remains of the walls of the last building phase. It is adjacent rectangular spaces destined to house the soldiers and for other uses (warehouses, kitchens, etc.).

When large structures such a castle exist in seismically unstable regions, the activity of faults or fault systems in and around the sites must be assessed. The walls of the Fragokastello castle are crossed by many cracks. There are various possible causes for these damages. The maintenance and restoration of damages represent a special challenge at the present time as well. Maintenance and restoration is a common problem of historical stone structures since they are under protection for their historical value. Building stones have widespread use in historic monuments which may provide unlimited durability if adequate conservation methods are applied; however it is well known that the great diversity of their nature often impairs the choice of the most suitable maintenance procedures. To control the stability and to verify the load-bearing capacity of the castle there are several modeling methods from the simple approximate calculations to the difficult numerical methods. With the ultimate goal to investigate the geotechnical conditions of the castle, aim of the present work is the characterization due simple statistical analysis various lithologies of the building stones of the masonry (Odysseus, 2016).

2. Geological setting

The Hellenides as part of the Alpine-Himalayan Orogenic Belt have been interpreted traditionally in terms of north directed convergence between Africa and Europe. The island of Crete is located north of the Hellenic trench and is a complex horst structure within the present forearc in the upper plate, on top of the shallow portion of the active Eastern Mediterranean collision zone. The island of Crete is one of the most seismically active area in the eastern Mediterranean. Tectonic uplift started since about 0.6 Ma as documented by Middle–Late Pleistocene marine terraces and Holocene raised notches along the coasts of the island and, on land. Normal faults typically consist of 4–30-km-long dip slip segments locally organised in more complex fault zones. They separate carbonate and/or metamorphic basement, in the footwall block, from Neogene, but especially loose to poorly consolidated alluvial and colluvial materials on the top of the hangingwall. All these faults show clear evidences of recent re-activations and trend parallel to two principal directions: WNW–ESE and NNE–SSW (Caputo *et al.*, 2010 and references therein). The activity of these faults created the Sfakian piedmont, a 24 km-long and 1.5 to 2.5 km-wide east–west trending coastal plain. The northern margins of the coastal plain are defined by the Sfakia fault zone that cuts across the lower slopes of the Lefka Ori mountain range. The footwall area of the Sfakia fault comprises mainly marble of the Plattenkalk Group and Trypali Unit. The western hangingwall area is dominated by alluvial fans along the mountain front. To the east the existence of phyllites on the hangingwall area of the Sfakia fault indicates significant vertical displacement (throw) of this fault. A complicating factor for calculating throws is the existence of the Fragokastello normal fault (Skourtsos *et al.*, 2007) which runs oblique to the Sfakia fault and terminates against it (Figure 1) (Nemec and Postma, 1993; Tsimi *et al.,* 2007; Skourtsos *et al.,* 2007; Pope *et al.,* 2008).

The coastal area between Chora Sfakion and Skaloti are covered by Neogene to Lower Pleistocene marine deposits (IGME, 1987) partly covered by Middle (?) Pleistocene -Holocene alluvial fans. These post-alpine deposits overlie the alpine basement with an angular unconfonnity. Three main marine sequences can be distinguished based on lithostratigraphy mapping. In stratigraphic order these are: the Skaloti Formation, the Chora Sfakion Formation and the Frangokastelo Formation. The Frangokastelo Formation occupies the central part of the coastal zone (Skourtsos *et al.*, 2007). The stratigraphic position of the formation is uncertain. It has been tentatively placed in the Middle Pliocene by Meulenkamp (1969) and the same outcrops were dated Late Pliocene by van Hinsbergen and Meulenkamp (2006). After Skourtsos *et al.* (2007) the Frangokastello Formation are much younger than previous age estimates. Using calcareous nannofossils an Early Pleistocene age for the Frangokastello Formation was determined.

As shown in Figure 2, in a position south of the castle exists a sequence that comprises of limestones with pebbles, both rounded and angular, with intercalations of sandstones, clays and clayed marls, such as the sequence reported by Meulenkamp (1969) in the village of Agios Nektarios.

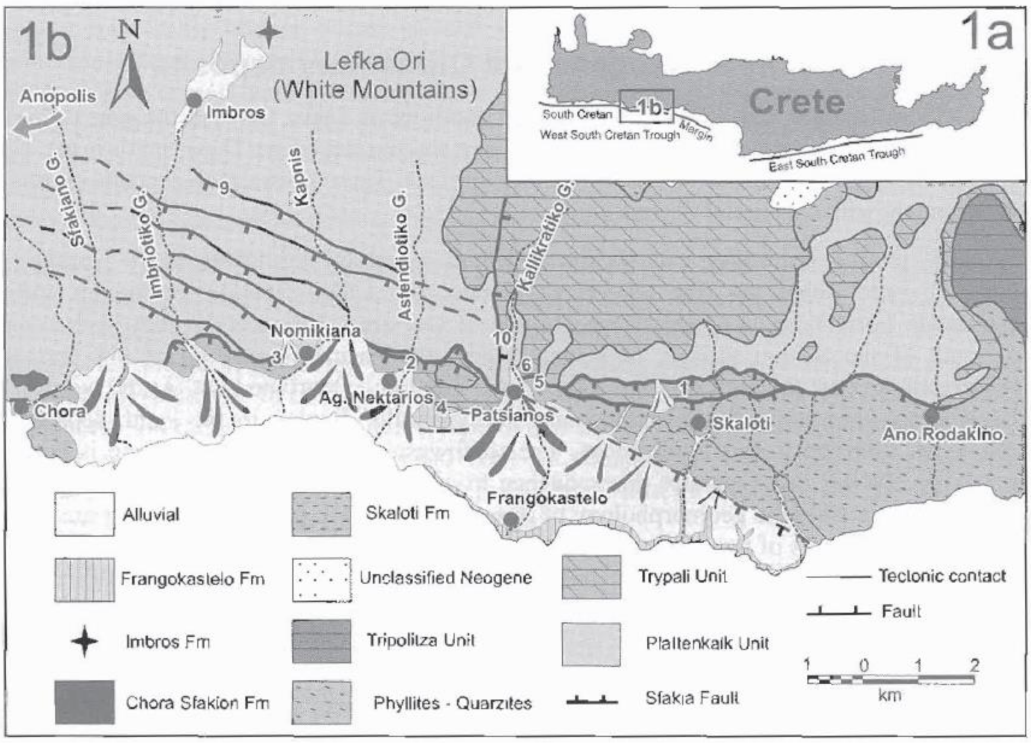

Figure 1 - a) Geological sketch map of the study area modified from I.G.M.E. (1982, 1987). b) The Sfakia coastal zone represents an onshore segment of the South Cretan margin (after Skourtsos *et al.*, 2007, modified from Alves *et al.*, 2007).

Figure 2 - Section at the cliff south of the castle: transition of clastic sedimentation (sandstones, microconglometates with intercalations of clays and clayed marls) to limestones with pebbles and bioclastic limestones.

3. Materials and Methods

The masonry of Frangokastello is composed of rocks with various lithologies including different forms of carbonate and clastic sediments. The materials are originated from the vicinity of the building, from the nearby alluvial fan deposits. Sedimentary rocks such as sandstones and (micro) conglomerates were also identified. Several forms of stones are used as masonry materials. Besides cut blocks of marble of the Plattenkalk Group, rounded cobbles of (meta)dolomites of the Trypali Unit form also a significant part of the masonry walls. Porous limestone has wide variety in fabric, porosity and poresize distribution (Figure 3).

Figure 3 - Various rock types in the masonry walls.

Aiming at a statistical quantification of the various lithological types of the rock fragments that were used to construction of the castle, we performed the following steps:

Firstly, we choose an appropriate area, i.e. the southern wall of the castle, where the mortar coating has been eroded. As a result of the erosion the building rocks are visible and measurable. Thus, it was reliable for the counting of rock fragments and subsequently for the statistical analysis on these constructions materials. In particular, we used a high resolution image (scale 1:100) of the south wall (Figure 4), in order to imprint the various lithologies of the building stones.

Secondly, image processing was utilized by AutoCAD software as follows:

(i) We designed the outlines of building stones in a selected wall surface with dimensions 22,67×2,19 m, which is situated about 30 cm above the ground surface, so that it is easy to have access to the area in order to identify and count the rocks (Figure 4).

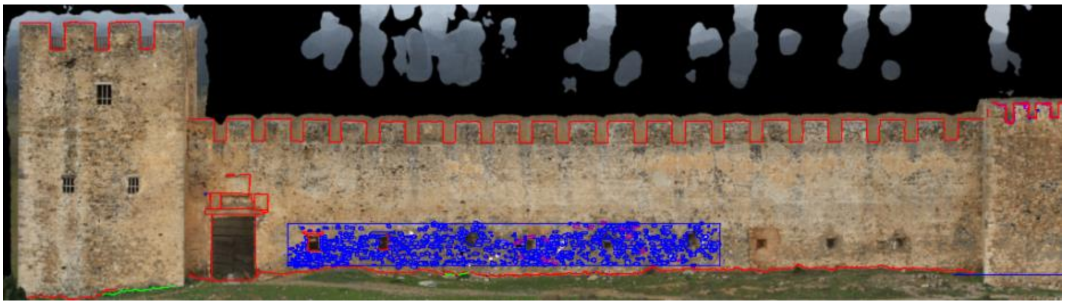

Figure 4 - The south wall designed with the outlines of the building stones of various rock lithotypes in selected area with dimensions 22,67×2,19 m.

(ii) We printed in scale 1:100 on paper A0, the image of the surface including all visible and measurable outlines of the building stones.

(iii) In situ observations considering the lithology led to the identification and counting of each bui lding stone within this area. Different lithologies highlighted with different colours.

(iv) Due to discrimination problems of two cement types, such as coating and binding cement, we performed a simple calculation using AutoCAD software. Specifically, the different lithology of the building stones (e.g. dolomites, sandstones), as well as the two cement types were imprinted in the paper, and converted manually with the aid of AutoCAD in their corresponding colours. The generated AutoCAD electronic file allows further correlations and calculations.

Figure 5 illustrates the final result of the differentially coloured lithologies of building stones within the selected surface on the southern wall of the castle. In the same surface, there are two smaller areas, in which the percentage of the binding cement was approximately calculated. The selection of surfaces A and B was done with the criterion that within these there are not smaller in size building stones which could not be registered. The total area of each surface is in square meters (m^2). The percentage participation of the binding cement in relation to the total surface area of each surface A and B calculated indirectly and automatically with the command AREA in software AutoCAD. For the surface A coverage of the mortar is 0,32 m^2 and 0,4 m^2 for the surface B. Therefore the percentage of the total surface area of the covered by the binding cement for surface A and B are 31.76% and 40.18% respectively, with a mean value at 35.95%. The results for areas A and B are presented in detail on the following Table 1. Table 2 shows the areas of building stones in m^2 and percentages in %.

Table 1 - Calculation table for Binding Cement.

	Surface A		**Surface B**	
	Surface Area m^2	**Percentage %**	**Surface Area m^2**	**Percentage %**
Sandstone	0,0157	3.2	0	0
Dolomite	0,0767	15,65	0.1086	22,16
Conglomerates	0.0393	8,02	0.0485	9,9
Micro Conglomerates	0,0892	18,2	0.0815	16,63
Biogenic Limestones	0,1036	21,14	0,0253	5,16
Limestones	0.0089	1,82	0.0259	5,29
Binding Cement	**0,1555**	**31,73**	**0,1969**	**40,18**
0,49	100		0,49	100

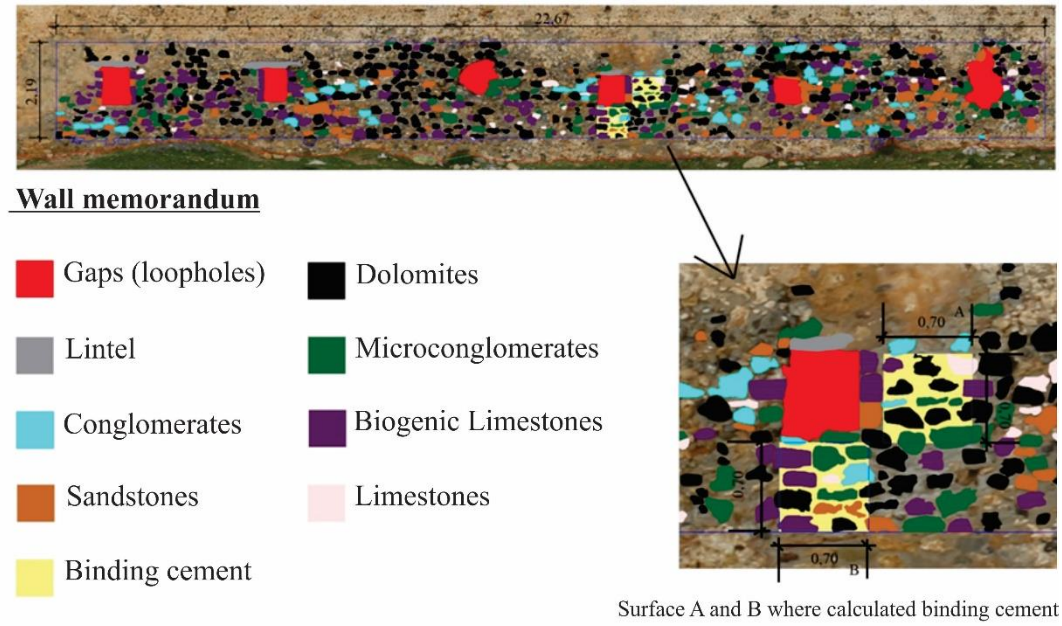

Figure 5 - View of the surface in which were made the counts and calculations. The various lithological visualized in the above memorandum in different colours based on the colour scale. At the bottom right the surface A and B used as an approximation calculation of the binding cement.

On the selected surface, as described above, the superficially percentage occupied on the wall by various lithological building rocks types was calculated. The surface area of the parallelepiped is 49.70m^2. Besides of the different lithological building rock types this area contains gaps (loopholes), the lintel of the gaps (loopholes) and both types of cement, the binding cement and coating cement. Table 2 presents in detail the areas of each surface and the percentage in 49,70 m^2 of the total area.

Table 2 - Cover surface and percentage of building rock types which used for construction of the castle

Study Surface	Surface Area m^2	Percentage %
Sandstone	1,94	3,90
Dolomite	6,98	14,04
Conglomerates	1,38	2,77
Micro Conglomerates	2,65	5,33
Biogenic Limestones	3,50	7.04
Limestones	0,45	0,91
gaps (loopholes)	2,76	5,55
lintel of the gaps (loopholes)	0,36	0,72
Coating cement + Binding Cement	29,63	59,62
Total Surface	**49,70**	**100**

The surface area of the binding cement and coating cement were not calculated directly from software AutoCAD but indirectly by using the following formula.

Binding cement and coating cement= total surface area-(sandstones surface area + dolomites surface area + conglomerates surface area + limestones surface area + micro conglomerates surface area + biogenic limestones surface area + gaps (loopholes) surface area + lintel of the gaps (loopholes) surface area namely:

Binding cement and coating cement= 49,70-(1,94 + 6,98 + 1,38 + 2,65 + 3,5 + 0,45 + 2,76 + 0,36) = 29,63m^2

According to the above table, we demonstrate that building rock type with the largest percentage on the wall surface area is black dolomite (metadolomite of Trypali Unit) with a percentage 14,04 %, followed by biogenic limestone with a percentage 7,04%, micro conglomerates 5,33%, sandstone 3,90%, and conglomerates 2,77%. A small percentage have gaps (loopholes) 0,72%. The lowest percentage on the wall surface area belongs to the white limestone 0,91%.

4. Results

Frangokastello is a Medieval castle which was built by the Venetians in 1371-74 in a narrow coastal zone at the southeastern part of the White Mountains characterized by a strong morphological relief. The creation of the relief was formed by mobility of normal faults with general striking E-W, NNE-SSW and NNW-SSE. These various tectonic blocks were uplifted several times. By the effect of intense tectonic activity the coastal plain was covered by multiple accretions of alluvial fans.

Frangokastello castle has been built on the biogenic limestone of Frangokastello formation. Rounded and angular fragments of resistant rock materials from alpine and post alpine formations transported and deposited within the various parts of alluvial fan, which had deposited over the Frangokastello formation. The coarse clastic fragments of both formations (Fragokastello and alluvial fans), constituted the building stones for the construction of the castle. By the statistical processing of measurements of various lithological rock types which were used for the construction of the castle, building rock types with the largest percentage on the wall surface area is black dolomite (metadolomite of Trypali Unit) with a percentage 14,04 %. Followed biogenic limestone with a percentage 7,04%, micro conglomerates 5,33%, sandstone by 3,90%, conglomerates 2,77%. A small percentage have gaps (loopholes) 0,72%. The lowest percentage on the wall surface area belong by the white limestone (marble of the Plattenkalk Group) 0,91%.

According to the above data we may conclude:

(i) Metadolomite of Trypali Unit has been preferred as building stones from all the Pre - alpine rocks which were transferred by alluvial fans to the coastline. The reason for this was that they combine a high durability, since they are metamorphosed, but simultaneously the external surface is not smooth like most other metacarbonate rocks (e.g. calcitic marble of the Trypali Unit and the Plattenkalk Group).

(ii) In contrast, the rest of the building stones do not have a high durability, but they have relatively high primary porosity which allows a better connection to the binding cement.

The results of the first statistical approach of rock fragments, which were the building blocks in the construction of the castle, can be input data for static and dynamic analysis models of the structural system, under the proposals maintenance and restoration of the monument. From the recording of various lithological types of rocks used to build the castle confirmed the fact of the coexistence of many different materials in the same construction and the different types of engagement of these materials in different parts of the structure. This fact is an important problem in the choice of the mechanical characteristics of the masonry to be used in the structural analysis. The choice of these parameters for monumental constructions requires research even if there is a possibility of measuring the mechanical characteristics of the individual materials which make up the walls.

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