Microfacial Analyses on the Building Stones of the Maya Site of Calakmul

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Abstract

This article focuses on the petrographic and microfacial characterization of the building stones, buildings, monuments, and quarries of the archeological site of Calakmul to document aspects of composition, lithologies, and stone exploitation. Microfacial analysis shows that the used building rocks are highly recrystallized biosparudites (grainstones to packstones) with the presence of reef and shallow waters fauna (boundstones). These rocks have an intermediate porosity (10–20% pore volume values) and XRD analysis confirms that the mineral composition is mainly calcite, but also dolomite. Microfacies analysis demonstrate that limestone of the stelae and the SubIIc-1 main façade come from the same quarry and have fine texture corroborate that these stones are suitable materials for carving and lime production. Samples from St. XX Gran Acropolis and from Chan Chi’ich Group come from a different quarry. These results help us to know the origin of the rocks, their use in the different buildings and monuments studied, and to contribute to the knowledge of their lithological characteristics and their response to weathering and thus provide important information that will help in taking decisions in case of probable measures of restoration and conservation of the rocks in the Calakmul region.

Introduction

Limestone, a sedimentary rock composed of calcium carbonate (CaCO$_3$), is abundant in the Yucatán Peninsula and was the key regional material as a building stone for the Maya culture. Limestone has a medium density (2.5 to 2.7 g/cm$^3$), its hardness is acceptable, and normally it is easily polished and workable. Its geographic availability together with the ease with which it is carved and its good qualities in terms of its mechanical properties have made possible its use since Pre-Columbian times to build impressive cities and pyramids in harsh tropical landscapes. Also, limestone is the only type of outcropping rock on the Yucatan Peninsula.

Since early excavations, archaeologists have shown a particular interest in identifying the materials and construction processes of the buildings in the Maya area (Holmes, 1895; Morris et al., 1931). Studies based on ethnographical observations with quarrying have documented the main stages to obtain cut stones for construction (Ruiz-Aguilar, 1986; Woods and Titmus, 1994). Ethnographical comparison and experiments have also served to reconstruct operations and quantify labor in construction (Abrams, 1994; Abrams and Bolland, 1999). From this process, lime production (Abrams and Rue, 1988; Hansen, 2000; Schneider, 2002, Wernecke, 2008; Seligson et al., 2017; 2018), as well as the identification of mortars have had particular attention for archaeological interpretation (Villaseñor 2010; Gillot 2014; García et al. 2016; Straulino 2016). However, studies regarding the characteristics of the stones used for construction in the archaeological context are still an underexplored topic. This article aims to contribute to the petrographical, microfacial, and geochemical identification of the stone used for the construction and art of the Maya ancient city of Calakmul situated in the Mexican Peten region in the southern area of the Yucatan Peninsula, in the State of Campeche, Mexico in order to generate a basis for comparison with other examples in the region and clarify the provenance of some natural stones already identified. In this paper, the methodology used determines the mineralogical and lithological composition of the limestones.
from quarries and different buildings and monuments at Calakmul to show their variability, correspondence, quality for different processes of construction, and durability against deterioration.

Few studies have identified stones of buildings and monuments of archaeological sites in the south of Campeche and are focused on understanding deterioration processes, including Oxpemul within the borders of the biosphere of Calakmul (García & Valencia, 1997; Straulino 2012; Espinosa et al. 2021).

**Localization of Calakmul and its natural landscape**

Today, the Biosphere Reserve of Calakmul and the archaeological site is a cultural and natural World Heritage property, which are located in the southeastern portion of the state of Campeche, 220 Km 220 south of the capital city of Campeche and at the same time in the southermost portion of the Yucatan Peninsula, Mexico (Fig. 1). The mix of a low, medium, and high subtropical forest constitutes a rich area of flora and fauna particularly adapted to the seasonal conditions of the Petén region (Martínez et al. 2001:13). The ancient city of Calakmul emerged in this environment, achieving a long-standing period of occupation and architectural development (from 500 B.C.E to 1000 C.E). Calakmul is also identified by its sociopolitical role in the region mainly during the Late Classic Period (600–900 AD) (Martin and Grube, 2008; Carrasco, 2015). Currently, the archaeological site is protected within the limits of the Calakmul Biosphere Reserve, covering approximately 703,000 ha (Fig. 1).

**Geological Settings**

The Ancient Maya City and Protected Tropical Forests of Calakmul, Campeche sit in the emerged area of the Yucatán Platform. The Yucatán Peninsula is an extensive karstic plain (Gaona Vizcaino et al., 1985 in Suarez and Rivera, 1998), consisting of more than 1,500 m of limestones, dolomites, and evaporites (Weidie, 1985) overlying a Precambrian and Paleozoic crystalline basement (Yucatan-Block). The surface area of the exposed platform reaches 165,000 km² (Bauer-Gottwein et al., 2011).

The present position of the Yucatán Peninsula began at the end of the Triassic (approximately 200 million years ago), as part of the opening of the Gulf of Mexico (Salvador, 1991c). At the end of the Callovian the Yucatán Block reached the position it occupies today and since then was subject to only slow but continuous subsidence until the Plio-Pleistocene epoch, when it began to emerge. At the end of the Middle Jurassic, the Yucatán block was for the first time transgressed by marine waters in its northern portion, with which marine sediments began to be deposited, but with great influence of detritic-terrigenous contributions.

During practically all Cretaceous time, the slow subsidence of the Block continued, causing more and more deposition of carbonates, mostly from shallow waters. This carbonate sedimentation crossed the Cretaceous/Paleogene boundary, however by this boundary the presence of marls was increasingly noticeable (Lopez-Ramos, 1973).

At the end of the Pliocene and Quaternary the Peninsula acquires its present form, although large alignments of biostromal type reefs continue to develop to the north of the Campeche Bank, which is
formed essentially of calcareous material (Lopez-Ramos, 1973).

The karst is the main geomorphological feature of the Yucatan Peninsula, especially in the central-southern area, which began its formation during the Miocene and continues today (Lugo et al. 1992:146). Limestone dissolution has caused typical surface karst features such as dolines, uvalas and poljes. In addition, water infiltration has generated several gallery and cave systems as main subterranean karst forms, which have been alternatively subjected to phreatic and vadose zones because of eustatic sea-level fluctuations during the Pleistocene (Gascoyne, 1984:48).

In this tropical karst landscape, the area where Calakmul is located is basically a plain with hills of 400 m asl as maximum elevations (García et al. 2002:13). Specifically, the archaeological site is in a valley that is located on a NW-SE tectonic line (García et al. 2002:11) surrounded by hills of 20 to 50 m high with steep slopes and ravines. This depression allows channeling rainwater towards the plain, concentrating mainly in an enormous reservoir known as “El Laberinto”, which surrounds the Pre-Columbian settlement (Geovannini 2008, Fig. 2).

Stratigraphically Calakmul is situated on Paleocene strata constituted by limestone sequences interfingered with siltstones and claystones (Icaiche formation), as well as by anhydrite and gypsum deposits with some argillaceous horizons (Xpujil formation) (Castro 2002). These Paleocene limestones and Quaternary unconsolidated calcareous deposits are the main building materials used in the ancient city and its monuments. Figure 3 shows the regional geological map and the corresponding superficial stratigraphic column (Cenozoic sequence) (Castro 2002).

The archaeological data of Calakmul quarries

According to the settlement pattern study carried out by Universidad Autónoma de Campeche (UAC), 39 quarries were identified in Calakmul. The quarries varied a lot in size and depth. They fluctuate in area from 6.25 up to 3,000 m² and in depth from 0.8 to 3.5 m (Folan et al. 2001). Most of the quarries are in a range of 10 to 50 m away from the southeast and southwest sector of the site where domestic units and urban centers are mostly concentrated (Gallegos 1994).

Archaeological survey and excavations of three quarries identified by the UAC at Calakmul show some features that are consistent with ethnographic observations made in modern processes of stone block extraction in Guatemala (Ruiz-Aguilar 1986). The three quarries (Quarries I, II and III) located in the core of the site have deep vertical cuts as part of the preparation for block extraction (Gallegos 1994) (Fig. 4). Only Quarry III has various blocks in cutting process and other rectangular and square blocks of different sizes already detached near the rocky surface (Gallegos 1994).

The bedrock cut recorded in Quarry I reaches 1.70 m long, 0.5 m wide and 0.7 m deep. Made by the first archaeologists, they suggested that the block could be used to carve a stela (Morley 1970). However, this assertion has been questioned, because comparing the dimensions of the stelae on the site shows they are on average much higher (Gallegos 1994).
Another important feature to note was the presence of a 'stonewall' created by the continuous cut of blocks of stone in Quarry I and II. In Quarry II, a more sinuous cut in comparison to Quarry I was identified. Gallegos speculates that a clean cut was possible due the 'good quality of the stone' that allowed this type of work (Gallegos 1994). This comment could be suggesting that the stone was hard enough that it broke into pieces during the detachment process of the blocks.

The quarries also contained empty spaces between the layers of cut stones that are known as “sascaberías” or where “sascab” is obtained. “Sascab” is a type of stone powder obtained from desintegrated limestone strata used to make lime mortars (Estrada-Medina et al., 2019). These type of “sascaberías” related to quarries have also been reported at other Maya sites (Folan, 1978; Eaton, 1991).

**Materials And Methods**

Since these are historical buildings and monuments, it is difficult to obtain original samples for study. In spite of this our investigations includes the analyses of 11 natural building stones used in architecture and art from the archaeological site of Calakmul (Fig. 4). The samples were taken with the approval of the National Institute of Anthropology and History (INAH) through the Archaeological Calakmul Project as part of the activities of the conservation team during 2002–2004. The cut stone samples come from buildings blocks found during excavations that it was not possible to put back in the buildings during their restoration. Additionally, the stelae samples derive from sections that were already detached.

Three samples of three different quarries were analyzed. Two quarries are located in the north and northeast of the site close to the *Chiik Nahb* Group and the residential *Chan Chi'ich* Group (Fig. 4), and one quarry already identified by Góngora (1994) and registered as Quarry 3, which is in the surroundings of Structure 1 and its plaza (Fig. 4).

On the other hand, six cut stones analyzed correspond to three different architectural complexes at Calakmul that represent different important construction periods at the site; three samples from the Structure XX, two samples from the *Chan Chi'ich* Residential Group (both Late Classic Period 600–900 C.E.) and one sample from the SubIIC-1 main facade which is the earliest building identified at the site (Late Preclassic Period 450 – 150 B.C.E).

Finally, this study includes samples of two stelae, which are a vertical stone monolith that is generally carved on its four sides bearing hieroglyphic inscriptions and portraits of rulers in acts of self-sacrifice or showing captives. Calakmul has more than 150 stelae that are located in front of the main buildings and plazas. For this study, we sample Stelae 52 (sample 17P4) and Stelae 55 (sample 18P5) dated by 731 C.E. (Morley, 1970). Both are in the Structure 1 principal plaza (Fig. 4b y 4c).

In addition to including the macroscopic characteristics of the collected specimens, the petrographic studies include a microfacial analysis to determine the characteristics of the matrix, components and biota under the microscope. This method allows us to see similarities or differences between the different limestones studied and thus provide information regarding their origin and deposition zone so that with
the microfacial study we can also correlate the samples collected according to the quarry from which they were extracted.

Limestone classification requires the identification of grains called “allochems” (coated grains, peloids, aggregate grains, carbonate clasts and bioclasts), as well as the type of intergranular material: microcrystalline calcite (micrite matrix) or calcite crystals > 5 µm in size (spar cement). In this study, the classification used for the petrographic analysis is based on Dunham (1962) modified by Embry & Klovan (1971), and of Folk (1962), which are based on “fabric”, a term that includes textural as well as compositional criteria. Most fabrics reflect depositional controls or early diagenetic processes, so these classifications (based on depositional textures) prove especially successful for development of environmental interpretation models (Flügel 2004).

The petrographic characterization was performed by Petrography Microscopy, Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD). By analyzing the scanning electron microscope results, we are able to identify the components present in the stone. It provides information about the morphology and the chemical composition of minerals. Moreover, it serves to characterize the porous system, while X-ray diffraction is used to identify the mineral phases.

The petrography microscopes used are a polarization optical microscope for transmitted light with plane polarized light (PPL) and crossed polarized light (CPL) and a Carl Zeiss mirror light, model ‘Axiolab Pol’ adapted with a ‘KS” -300’, and a petrographic microscope Leica model DM LP. Unconsolidated or strongly deleterious samples are encapsulated in low-density resin under vacuum. Some properties such as density, porosity and absorption of the samples were determined by using hydrostatic weighting.

The XRD analysis was realized with a Siemens equipment D5000, Bragg-Brentano geometry. The diffractograms were recorded in the range of $5 \leq 2\theta \leq 60\degree$, with a step size of 0.02° and an integration time of 2s. Radiation was monochromatic CuKα ($\lambda = 1.5416 \text{ Å}$). The voltage of the X-ray tube was 35 kV and the current 25 mA. In order to identify minor components in calcium carbonate matrices, the samples first were treated with 5% (v/v) hydrochloric acid. Finally, a Phillips XL30 ESEM electronic microscope, coupled with an X-ray dispersive energy spectrometer, EDX, operated at 25 kV was used.

**Microfacial Description Of The Analyzed Stones**

**Quarries**

All the studied stones are carbonates, limestones, and dolomites. The three samples from the quarries were obtained directly from the outcropped surface. All of them had a crust with biological deposits (algae, lichens, and mosses). The rocks of the North and Northeast quarries had cream-color matrices, while the rocks of the quarry near Structure 1 showed a color variation with the presence of cream and ochre bands. The samples from the Northeast quarry showed a grained (sugaring) texture that did not vary in color from the matrix.
The North Group Quarry samples (codes 19P6, 20P7 and 21P8, Table 1, Fig. 4) show the following microfacial characteristics.

Table 1

<table>
<thead>
<tr>
<th>Provenance</th>
<th>Location</th>
<th>Sample code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarry</td>
<td>Northeast Group</td>
<td>19P6</td>
</tr>
<tr>
<td></td>
<td>North Group (Chiik Nahb)</td>
<td>20P7</td>
</tr>
<tr>
<td></td>
<td>Structure 1</td>
<td>21P8</td>
</tr>
<tr>
<td>Cut Stone</td>
<td>SubIIc-1</td>
<td>29P10</td>
</tr>
<tr>
<td></td>
<td>St. XX Gran Acropolis</td>
<td>31P11</td>
</tr>
<tr>
<td></td>
<td>St. XX Gran Acropolis (south annex)</td>
<td>32P12</td>
</tr>
<tr>
<td></td>
<td>St. XX Gran Acropolis</td>
<td>33P13</td>
</tr>
<tr>
<td></td>
<td>Chan Chi´ich Group</td>
<td>34P14</td>
</tr>
<tr>
<td></td>
<td>Chan Chi´ich Group</td>
<td>35P15</td>
</tr>
<tr>
<td>Stelae</td>
<td>E. 52</td>
<td>17P4</td>
</tr>
<tr>
<td></td>
<td>E. 55</td>
<td>18P5</td>
</tr>
</tbody>
</table>

Sample 19P6:

The hand sample shows a compact, medium gray to cream-colored rock with elongated pores distributed throughout the sample. The naked eye can recognize small angular fragments and some semi-rounded bodies, which are only recognized with the magnifying glass. Under the microscope, it is recognized that sample 19P6 contains 50% of the ground mass and 50% of the components. The ground mass is micrite, which is not very homogeneous and gives a disturbing appearance. Within the matrix, there is a primary fenestra porosity, which occurred during the deposition of the rock. The porosity reaches more than 10% (Fig. 5B). The components vary in size ranging up to 0.2 mm and some up to 2 mm (Fig. 5A). The largest components are bioclasts of various shallow-water organisms such as some pelecypods and some gastropods (30% of the components). More abundant with about 60% of the components are pellets with ovoid shapes (Fig. 5A), without internal structure, and composed of micrite. 10% of the components are some aggregated grains, intraclasts as well as sporadic small, rounded quartz crystals (Fig. 5A, 5B). The quartz does not give a detrital appearance and is probably autogenous quartz. Due to a large number of components the rock fabric is grain supported (Fig. 5B).

According to Dunham (1962), sample 19P6 is a packstone of pellets and bioclasts and according to Folk (1962), the sample is a Pelbiomicrude.
According to Flügel (2004), the rock is a RMF 23 (fenestral bindstone) of the peritidal zone or SMF 21 (spar-filled voids within a micritic or pelmicritic framework), of the platform interior restricted.

We can clearly observe by SEM its intercrystalline porosity and the long and concave-convex contacts of its components (Table 1, Fig. 4A).

Sample 20P7

Sample 20P7 show more than 90% of groundmass and less than 10% of components. The groundmass is of two types, a fine micritic matrix which under the microscope appears medium gray (Fig. 5C), and a very incipient microsparitic cementitious which is mixed and disorganized in the groundmass forming a dismicritic texture (Fig. 5D). The microsparite under the microscope looks clearer and with a microcrystalline habit, this differentiates it from the micritic matrix that looks almost opaque. No arrangement can be recognized in the basic mass and its porosity is lower than in the other samples from the quarries analyzed (Table 2).
<table>
<thead>
<tr>
<th>Type</th>
<th>Location</th>
<th>Sample code</th>
<th>Allochems (%)</th>
<th>Matrix / cement (%)</th>
<th>Porosity (%)</th>
<th>Dunham Classification</th>
<th>Facies Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarry</td>
<td>Northeast Group</td>
<td>19P6</td>
<td>50</td>
<td>50</td>
<td>20</td>
<td>Packstone</td>
<td>Peritidal zone of the inner ramp</td>
</tr>
<tr>
<td></td>
<td>North Group (Chiik Nahb)</td>
<td>20P7</td>
<td>10</td>
<td>90</td>
<td>10</td>
<td>Mudstone</td>
<td>Lagoon of the inner ramp</td>
</tr>
<tr>
<td></td>
<td>Structure 1</td>
<td>21P8</td>
<td>20</td>
<td>80</td>
<td>20</td>
<td>Mudstone</td>
<td>Lagoon of the inner ramp</td>
</tr>
<tr>
<td>Cut Stone</td>
<td>Subllc-1</td>
<td>29P10</td>
<td>70</td>
<td>30</td>
<td>20</td>
<td>Dolopackstone</td>
<td>Peritidal zone of the inner ramp</td>
</tr>
<tr>
<td></td>
<td>St. XX Gran Acropolis</td>
<td>31P11</td>
<td>10</td>
<td>90</td>
<td>15</td>
<td>Wackestone Packstone</td>
<td>Sand shoals and banks</td>
</tr>
<tr>
<td></td>
<td>St. XX Gran Acropolis (south annex)</td>
<td>32P12</td>
<td>50</td>
<td>50</td>
<td>20</td>
<td>Packstone</td>
<td>Boundstone</td>
</tr>
<tr>
<td></td>
<td>St. XX Gran Acropolis</td>
<td>33P13</td>
<td>40</td>
<td>60</td>
<td>12</td>
<td>Packstone</td>
<td>Inner ramp – mid-ramp</td>
</tr>
<tr>
<td></td>
<td>Chan Chi´ich Group</td>
<td>34P14</td>
<td>30</td>
<td>70</td>
<td>15</td>
<td>Wackestone Packstone</td>
<td>Lagoon of the inner ramp</td>
</tr>
<tr>
<td></td>
<td>Chan Chi´ich Group</td>
<td>35P15</td>
<td>30</td>
<td>70</td>
<td>15</td>
<td>Wackestone Packstone</td>
<td>Lagoon of the inner ramp</td>
</tr>
<tr>
<td>Stelae</td>
<td>E. 52</td>
<td>17P4</td>
<td>10</td>
<td>90</td>
<td>15</td>
<td>Dolomudstone</td>
<td>Lagoon of the inner ramp</td>
</tr>
<tr>
<td></td>
<td>E. 55</td>
<td>18P5</td>
<td>40</td>
<td>60</td>
<td>40</td>
<td>Dolowackestone</td>
<td>Peritidal zone of the inner ramp</td>
</tr>
</tbody>
</table>

The components that do not reach 10% of the total sample are mainly small bioclasts, remains of some unidentifiable pelecypods, gastropods, and brachiopods (more than 90% of the components). Locally, some small benthic type foraminifera is recognized but they are very scarce. Embedded in the matrix are
some zones with small iron oxide crystals that locally are found in clusters or frambooidal forms (Figs. 5C,5D).

According to Flügel (2004) sample, 20P7 has a standard microfacies RMF 19 (non-burrowed lime mudstone) from the facies zone (FZ) of the lagoon to the peritidal area of the inner ramp (Table 2).

Sample 21P8

Sample 21P8 is composed of more than 80% groundmass and less than 20% components. The groundmass is microcrystalline calcite (micrite) and is light gray to cream-colored. The matrix has in general an inhomogeneous disturbing appearance (Fig. 5E, 5F). Under the microscope, no internal structures or arrangements of the matrix are recognized and due to its microcrystalline habit, the matrix looks of very variable shades. Within the matrix, very high porosity is recognized (> 20%), with elongated pores, many of them interconnected. These are fenestral pores (Fig. 5F primary depositional) that can be caused by shrinkage parallel to stratification or by leading to bubbles through degassing for evaporation and also putrefaction of organic matter (Fig. 5E).

The components are randomly distributed within the matrix and are mainly bioclasts, mainly unidentifiable bivalves, and some pellets. Sample 21P8 is very poor in microfauna. Small intraclasts (Fig. 5F), and occasional quartz crystals, probably detrital, occasionally occur embedded in the matrix. The fabric of sample 21P8 is mud supported and is classified according to Dunham (1962) as a mudstone / wackestone and according to Folk (1962) as a micrite / biomicrite (Table 2).

The deposit zone of sample 21P8 is very similar to that of sample 20P7, with the difference that the porosity of this sample is higher, caused very probably by the higher evaporation rate. According to Flügel (2004) sample, 21P8 has a standard microfacies RSM 19 (non-burrowed lime mudstone) from the facies zone (FZ) of the lagoon to the peritidal area of the inner ramp.

In terms of composition, by XRD, the quarry samples show that calcite peaks as bulk material dominate but different amounts of dolomite are also recognized in the three samples (Fig. 6). Other minor components must be masked by the high content of calcite such as the quartz identified by petrography.

Building cut stones

Sample 29P10

The principal façade of the oldest building identified at Calakmul by now (Subllc-1, Table 1), has this type of limestone.

The sample is composed of 70% groundmass and 30% components. The groundmass is medium to dark gray and in polarized light appears almost black. It is composed of microcrystalline calcite (micrite) partially homogeneous and even peloidal locally. Within the matrix there is an important amount of thin and elongated pores, many of them are "ghosts" of dissolved bioclasts (moldic porosity, Fig. 7C).
The components, 30% of the sample, are mostly bioclasts of different organisms (coral-algal, gastropods, brachiopods, and lamellibranchs, Fig. 7A, 7B). Microfauna is poorly represented. An interesting aspect of sample 29P10 is that it shows selective dolomitization, where only some bioclasts, mostly large bioclasts, are replaced by dolomite. The characteristic rhombohedrons of dolomite are visible in some specimens. The small size of the dolomite crystals suggests early replacement.

Although the bioclasts and the general habit of the rock suggest shallow depositional environments, it was not possible to recognize reef-forming organisms (corals), so it is assumed that there was a ramp and not a rimmed platform.

The rock fabric varies locally from mud- to grain-supported. The rock can be classified as packstone, dolopackstone (Dunham, 1962) or biomicrudite (Folk, 1962) and according to its ramp microfacies type it is a RMF 26 Bioclastic packstone with diverse skeletal grains of the peritidal zone of the inner ramp (Flügel, 2006).

By EDS, the micrite and some dolosparite are well defined as rhombohedrons of different sizes as clumps or isolated within bioclasts structures (Fig. 7C). García et al. (2016) shows that the cut stones of SubIIc-1 facade by XRD analysis have also montmorillonite. This configuration made of this stone a low-density material with low resistance to pressure and hardness as has been identified before.

On the other hand, the cut stones of Structure XX of the Gran Acropolis and Chan Chi’ich Group have more elements in common than the sample discussed above (SubIIc-1). Four of the five samples analyzed have approximately half of micrite matrix and half of allochems, with sporadic small non-carbonate grains (quartz fragments, opaque minerals, etc.). These samples are:

**Sample 31P11**

Sample 31P11 of the St. XX Gran Acropolis consists of 90% groundmass and 10% components, although the local percentage of allochemicals can reach 30% of the rock.

The groundmass is composed of microcrystalline calcite (micrite) in a matrix that locally is mixed with sparite microcrystals making a dismicritic texture (Fig. 8A, 8B), but micrite dominates in the sample. In the matrix, there is an important number of pores that exceed 15% of the whole of the sample. The porosity is primary and is not a product of diagenesis.

The components that become very scarce in some parts of the sample, similar to the previously described samples, are mainly composed of bioclasts, however, unlike the others, in this sample, they are partially homogenized by micritization, a product of algal perforating activity (Fig. 8A).

The fabric of the sample is mud-supported and is classified as wackestone /packstone (Dunham, 1962) or biomicrite / biodismicrite (Folk, 1962) from a RMF 27 type, bioclastic packstone with a few dominant skeletal grains from the sand shoals and banks of the inner ramp.

**Sample 32P12**
Sample 32P12 of the St. XX Gran Acropolis (south annex), consists of 50% groundmass and 50% components. The groundmass is dark gray microcrystalline calcite in natural light and appears almost opaque under polarized light. The micrite is very fine-grained and only in very punctual zones, some incipient recrystallization to microsparite can be seen (Fig. 8D).

The components, about 50% of the sample are composed of macroorganisms, all inhabitants of reef zones, and are mainly corals, coralline algae, bryozoans, algae, and other inhabitants of reef and peri-reef zones (Fig. 8C, 8D). Although the presence of reef-forming organisms is clear, they are not recognized as being in situ, as they are partially fragmented and in chaotic positions, indicating that they are transported and reworked to the peri-reef zones.

The sample shows a large number of pores (> 20%, Fig. 8D), mostly intercrystalline and moldic primary porosity. Sample 32P12 has a grain-supported fabric and does not appear to be associated with any boundstone or reefal framework.

This limestone can be classified as a boundstone (Dunham, 1962) or biolithite (Folk, 1962) and would correspond to RMF 12, from the open marine zone at the boundary between the inner ramp and mid-ramp, where occurs occasionally scattered corals (Flügel, 2004).

Sample 33P13

This sample, also from the St. XX Gran Acropolis (Fig. 4), shows a greater number of components than sample 32P12. In this case, sample 33P13 consists of 40% groundmass and 60% components.

The groundmass is a dark gray micritic matrix, almost opaque in polarized light, which serves as a binder between the components of the sample. The remaining 60% of sample 33P13 are macrofossils arranged as coquina, although locally they give the appearance of being a reefal framework (Fig. 8E).

The components are coralline algae (?) in 90% and the remaining 10% are bioclasts of braquiopods, some mollusks and benthic foraminifera that are located in the cavities of the corals. The porosity of the sample is good (around 15%) and is of the interparticle (primary) and moldic (secondary) type (Fig. 8F).

Sample 33P13 is classified as a boundstone (Dunham, 1962) or as a coral biolithite (Folk, 1962).

This microfacies corresponds to an RMF 12 (boundstones comprising coral and coral-crust framestone, red algal framestone) of the boundary between the inner ramp and mid-ramp (Flügel, 2004).

The samples of the Chan Chi’ich Group (Table 1, Fig. 4), differ from the samples from the Greater Acropolis area in the matrix / component relationship, as well as in their faunal content. Two samples from the Chan Chi’ich Group were analyzed.

Sample 34P14
Sample 34P14 is limestone with 70% groundmass and 30% components and shows a large number of pores distributed irregularly throughout the sample.

The groundmass is micrite, but mainly microsparite and they are gray to dark beige in color (Fig. 9A). In polarized light, the matrix appears light gray microcrystalline unlike the previous samples, where the matrix appears dark or semi-opaque due to micrite.

The matrix has an inhomogeneous, partially disturbed, and homogenized appearance with light and dark zones within it (Fig. 9B).

The components are practically only bioclasts, which are small fragments (0.2 to 0.5 mm), of organisms with thin shells and remains of coralline algae, gastropods, bivalves, as well as some benthic foraminifera, all of them characteristic inhabitants of shallow waters.

The porosity dispersed throughout the sample gives the rock a fenestrated texture, which suggests shallow, hot environments with high gas production products of evaporation and decomposition of algae and cyanobacteria. The fabric is mud-supported.

Sample 34P14 is classified as a fenestral wackestone/packstone (Dunham, 1962) or fenestral biomicrite (Folk, 1962), with a microfacies standard, RMF 20, bioclastic wackestone/packstone with algae and benthic foraminifera from the lagoonal zone of the inner ramp at the edge of the shoal zone.

Sample 35P15

Sample 35P15 is very similar to the previous sample 34P14 and consists of 70% groundmass and 30% components. The groundmass is composed of a micrite matrix, which is partially recrystallized in microsparite giving it a locally dismicritic texture (Fig. 9C, 9D). The matrix appears dark to semi-opaque where micrite dominates and where microsparite dominates it is lighter and microcrystalline. The matrix is locally disturbed, suggesting homogenization by organic activity and by movement and reworking of the sediment.

The components are mostly elongated and thin clasts (bioclasts) of reef-forming organisms, such as coralline algae, some bivalves, and gastropods, which are coated to varying degrees (coated grains). Some bioclasts are completely micritized and occur as pseudopellets within the matrix.

As in the previous sample, there is a large number of pores randomly distributed throughout the sample. Some pores are elongated, suggesting a secondary porosity of the moldic type and giving the sample a fenestral texture.

Sample 35P15 has a mud-supported fabric and is classified as a fenestral wackestone/packstone (Dunham, 1962) or fenestral biomicrite (Folk, 1962), with a microfacies standard, RMF 20, bioclastic wackestone/packstone with algae and benthic foraminifera from the lagoonal zone of the inner ramp at the edge of the shoal zone.
Stelae

Stela E.52 (Table 1) is mutilated in two of its faces, leaving only a row of glyphs on its sides with no visible loss pattern that can be associated with its mineralogical characteristics (Fig. 3B). A clean cut and smooth surface are observed. In contrast, the Stela E.55 is a rectangular monolith with rounded edges and origin deformations. From a conservation point of view, this stela was worked from a 'poor quality stone' due to the generalized and differentiated superficial loss of the rock in the form of strata or gaps that make most of the representations illegible (García-Solís, 1999). Unlike E.52, the rough texture of E.55 is notable for constant weathering and detachment of clasts. An exception is an impressive gap at the top that reaches around 10 cm (Fig. 3C). In this case, the carving of the glyphs where it is located follows this disruption, which indicates its presence since the obtention of the stone.

Petrography shows the opposite it was observed at E.55. Both stelae were carved from finely textured stones.

Sample 17P4

In the two samples, the percentage of micrite matrix associated with clayey material makes up the majority compared to the presence of some lithics and microsparite matrix (Figs. 9A and 9C).

Microfacially, sample 17P4 corresponding to Stela E52 is composed of more than 90% of the groundmass and less than 10% of components. The groundmass is a very homogeneous micritic matrix where no orientation or arrangement is recognized. The components are scarce and are mainly small bioclasts of unidentifiable organisms, some rounded intraclasts (pellets?), and distributed throughout the matrix some iron oxide crystals are recognized (Fig. 9A). Also distributed throughout the matrix there is a significant number of unfilled pores, in shapes varying from round, elongated and in the form of "Bird-eyes". The fabric of sample 17P4 is clearly supported (Fig. 10B). This sample was classified as mudstone (mud-supported fabric that contains less than 10% grains).

Sample 18P5

Sample 18P5 from Stela E55 (Table 1, Fig. 4) contains 60 to 70% groundmass and 30 to 40% components. The groundmass is a peloidal micritic matrix that shows some disturbance. Unlike sample 17P4, in this sample, there is a higher porosity not only in percentage but also in pore size, since the pores are elongated, locally reaching lengths of up to 1 mm long. The elongated appearance of the pores allows us to consider them as "Bird-Eyes" and fenestral type structures. Some pores are being recrystallized with sparitic cement in the form of "dog-teeth" (Fig. 10F).

The components reach 40 percent of the total of the sample, being pellets the most abundant, followed by intraclasts, bioclasts, coated grains and some iron oxides and small quartz crystals (autigen), both late diagenetic.

The fabric of sample 18P5 is mud-supported but locally becomes grain-supported.
As seen by EDX, the recrystallized bioclasts by well-defined rhomboidal crystals of microsparite and dolomicrite preserved the original shape, but also has some more amorphous material that shows an increase of silica.

The composition of the stones used for the stelae by XRD shows the presence of dolomite as bulk material. E.55 was confirmed this result by EDX, the cement area has an almost equal proportion of Ca (16.57%) and Mg (11.15%) (Fig. 11). On the other hand, aragonite was also identified in the same sample by EDX. This finding implies that some organisms preserved their original composition, despite the advanced selective dolomitization (and recrystallisation) of most of the bioclasts of the rocks present (Fig. 10F).

Sample 18P5 shows the characteristics of a microfacies standard (RMF) 22, “Finely laminated dolomitic or lime mudstone” belonging to the peritidal zone of the inner ramp. The presence of bird-eyes and recrystallization to dolomite confirms its depositional zone.

**Discussion**

The rocks identified at Calakmul are frequent in marine platforms sequences formed in shallow reef areas. The type of bioallochems and the patchy cementation are diagnostic of this kind of sedimentation environments (Tucker, 1991). Dunham classification is necessary to know how many components there are and how they are distributed in the rock. This gives names according to the texture, which implies, percentage and size of allochems, packing and percentage of intergranular material (matrix or cement). By texture, the stones are much more varied (Table 2).

The result of the petrography shows that all the limestones studied were deposited in shallow water zones; however, with the help of the microfacial analysis, it is possible to define with greater precision the zones where they were finally sedimented. Additionally, the study of the macro and microfauna indicates that the rocks studied and used in the Calakmul buildings and stelae were deposited on a "ramp" type marine platform (Flügel, 2004), since there was no evidence of a typical reef margin for platforms with a reef edge (rimmed shelf).

Three depositional zones were identified with the Calakmul rocks (from deepest to shallowest) (Fig. 12). 1) the boundary zone between the mid-ramp and inner-ramp (samples 32P12, 33P13, and 35P15), 2) the area of sand shoals and banks of the inner-ramp (samples 31P11 and 34P14) and 3) the peritidal zone of the shallower edge of the inner ramp (samples 17P4, 18P5, 19P6, 20P7, 21P8 and 29P10) (Fig. 10).

The textures encountered vary from mudstone (micrite), wackestone (bimicrite), packstone - grainstone (bimicrodite, biosparudite) to boundstone - bindstone (biolithite) (compare with Table 2).

The microfacial study allowed us to make conjectures about the provenance of the rocks used in Calakmul. Limestones from three quarries were analyzed and it was shown that all three quarries belong to a similar facies zone (peritidal zone, Fig. 12), with textures dominated by a micritic matrix and good porosity, all three samples from the quarries are incipiently dolomitized (Fig. 6). The microfacial analysis
also showed that the rocks of the two stelae studied have the same facial characteristics as the rocks of the quarries studied and both are in different intensities dolomitized, so it is deduced that the rock of the Stela 55 came from the quarry near the St. I where it is located. An interesting fact is that similar quarries were probably the first to be exploited for the construction of Calakmul, since the sample of the SubIIc-1 main facade (29P10), the oldest construction of Calakmul, has the same microfacial characteristics as the rocks of the stelae and the quarry of St. I (Fig. 10).

Another relevant aspect is that for the construction of Structure XX Gran Acropolis and the Chan Chi’ich Residential Group, rocks from the quarries studied were not used, since they were erected with completely different rocks (reef limestones, boundstones, Fig. 10). The quarry or quarries from which the rock was extracted for the construction of these structures have not yet been found.

As Table 2 shows, there are different groups of textures due to the variations of percentage of allochems, matrix, cement and porosity of the samples between architectural complexes and chronological periods. One group congregates the stones of Chan Chi’ich and two of the three stones from Structure XX of the Gran Acropolis that have in common an advanced process of microsparite recrystallization of the bioclasts they contained. Both groups are located in the northern part of the city close to each other and correspond to the same chronological period in a span of 300 years. For that reason, the differences in the stones of both residential complexes could be related to the different stages of construction.

Another visible aggrupation is Stelae 55 (Sample 18P5) and Structure 1 Quarry (Sample 21P8). Both also have a similar texture and crystal disposition due to elongated relics of algae. These characteristics not only corroborate that the stone used for the stelae was an extract from Quarry I, also the preference of a close location to the selection of a specific type of rock. Even though both stelae have a fine cementation that allows the carving of glyphs and rulers’ portraits, the visible irregularities and the loss of material in gaps implies that the block obtained from the quarry on the macro scale does not have a homogeneous texture.

As the archaeological evidence suggests, quarry exploitation at Calakmul was inherently a process of architectural planning. A large number of quarries have been reported at Calakmul, and most of them are located in the area of architectural concentration (Folan et al. 2001). As described by Góngora (1994), the tools and hand-made cuts in the quarries indicate that natural outcrops were used to extract materials for construction. Outcrops were exploited to obtain stone and “sascab” as raw materials and lime production for building, but also the stone and debris were used to level the karstic landscape before the construction of plazas and architectural complexes. For example, most of the North Group or Chiik Nahb is located on a leveled outcrop as far as the northeast corner, where the outcrop of the North Group Quarry starts (Anaya 2019: personal communication), so it can be inferred that was exclusive for their construction.

The abundance of Calakmul's stony materials available for construction made quarry exploitation a non-intensive activity, but dependent on the volume of stone required for the architectural projects at a specific location. The presence of archaeological tools in the quarries not only illustrates stone exploitation but also evidence of the abandonment this activity.
Conclusions

The geological characteristics and composition of all the stones analyzed of Calakmul are convenient for building processes and no specific selection was required. The high porosity and calcite/dolomite content made of most of these materials soft enough to be easily worked and suitable to make lime, but not very resistant to exposure to the subtropical weather of the region. Intrinsic conditions such as the porosity (10–20%), and the heterogeneous matrices made these materials more sensitive to weathering and decay.

Not all the current texture visible of the stones used in Calakmul derives from a weathering process after its construction stage; some such as the one used in the stelae have irregularities since their acquisition. Stelae 55, a massive stone monolith, integrates in its carving some of the irregularities of the stone, since it was obtained from Quarry I. This also indicates that artists and builders of Calakmul were more interested in reducing the transportation costs of the stony materials in terms of human effort rather than to find a type of stone with a homogeneous surface. Records shows that stelae in St. IV in Calakmul have traces of red painting (García, 1999); this observation reinforces the idea that any stone could be used for carving, which implies in turn that, after carving, they were also covered with a stucco coating and pigments, thereby reducing in appearance the irregularities of the stone and protect the stone to weathering.

Some quarries as large surfaces of outcrops are still visible at nearby architectural complexes, and that corresponds to late construction stages at the site. In contrast, early sources might be completely exhausted, bringing important technological changes in the art building, such as the case of the earliest structure of Calakmul (SubIIc-1). The singular characteristics of stucco (extraordinary hardness and high density) used to decorate the SubIIc-1 are a consequence of the use of stones with high calcite contents to produce lime (cf. García et al. 2016).

Summarizing the conclusions, the microfacial petrographic study suggests that the rocks analyzed from the quarries were deposited in the same area where are located the different buildings sampled. Some quarries were most probably the first suppliers of construction materials since the oldest structure in the archaeological zone of Calakmul was made with reef limestone fabric that was more appropriate for that type of construction.

We also know now that the rocks of the great St. XX Gran Acropolis and Chan Chi’ ich Group complexes were built entirely with rocks from other quarries, that it has not been identified yet, clearly from a very different zone of deposition (mid-ramp, reefal limestones).

The restrictions on the number of samples that could be obtained from original materials were compensated by the span of the construction stages in Calakmul they represent. This allows a direct comparison of stones of the quarries and the buildings and monuments of Calakmul which offers new insights into the arid topic of stone archaeometry of quarries in Maya studies and stone exploitation in the karstic landscape of the Peten region.

References


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**Figures**
Figure 1

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