Revista de Arqueología Americana • 40 • 2022 • Artículos • 327-359
• ISSN (impresa): 0188-3631 • ISSN (en línea): 2663-4066
• DOI: https://doi.org/10.35424/rearam.v0i40.1401

Physicochemical analysis of limestone tools and their viability for the study of secondary lithic resources in the geological environment of the pre-hispanic site of Sihó (Yucatán)

Llorenç Pujol Pizà[1]

Recibido el 10 de julio de 2022; aceptado el 31 de agosto de 2022

Abstract

Sihó is a Prehispanic archaeological site located in the Northern Maya Lowlands at Yucatan Peninsula, where have been documented a considerable number of percussion and/or abrasive tools made from limestone cobbles, which are known like manuports (Clark, 1988). These artifacts have certain physical and chemical characteristics which may be symptomatic of a particular geological origin. The statistical treatment of data extracted by X-ray fluorescence gives us the possibility of discerning limestone materials from different geological formations, based on their proportion of silicon (Si), calcium (Ca) or iron (Fe). Together with a comparative calculation between sphericity indexes of this round cobbles, suggest it catchment at Ticul fault colluvial secondary geological deposits twenty km from the site.

Key words: *Sihó, secondary geological resources, elemental chemical traces, sphericity indexes, catchment strategies.*

---

[1] Postdoctoral Programme Fellow POSDOC, Universidad Nacional Autónoma de México (UNAM), Centro Peninsular en Humanidades y Ciencias Sociales (CEPHCIS), correo electrónico: llorenspujol2@gmail.com

Resumen

Estrategias de captación de recursos líticos secundarios en el entorno geológico del yacimiento prehispánico de Sihó (Yucatán) a través del análisis fisicoquímico de herramientas de caliza

Sihó es un sitio arqueológico prehispánico ubicado en las Tierras Bajas Mayas del Norte en la Península de Yucatán, donde se ha documentado un número considerable de herramientas de percusión y abrasivas hechas de cantos rodados de piedra caliza, conocidos como manuports (Clark, 1988). Estos artefactos tienen ciertas características físicas y químicas que pueden ser sintomáticas de un origen geológico particular. El tratamiento estadístico de los datos extraídos por fluorescencia de rayos X nos da la posibilidad de discernir los materiales calcáreos de diferentes formaciones geológicas, en función de su proporción de silicio (Si), calcio (Ca) o hierro (Fe). Junto con un cálculo comparativo entre los índices de esfericidad de estos cantos rodados, sugieren su captación en los depósitos geológicos secundarios coluviales de la falla de Ticul a veinte kilómetros del lugar.

Palabras clave: *Sihó, recursos geológicos secundarios, trazas químicas elementales, índices de esfericidad, estrategias de captación.*

Résumé

Stratégies de captation des ressources lytiques secondaires dans l’environnement géologique du site préhispanique de Sihó (Yucatan) à partir de l’analyse physico-chimique des outils calcaires

Sihó est un site archéologique préhispanique situé dans les terres basses mayas du nord de la péninsule du Yucatán, où un nombre considérable d’outils de percussion et d'abrasion faits de galets de calcaire, connus sous le nom de manuports (Clark, 1988), ont été documentés. Ces artefacts présentent certaines caractéristiques physiques et chimiques qui peuvent être symptomatiques d’une origine géologique particulière. Le traitement statistique des données extraites par la technique de fluorescence de rayons X nous donne la possibilité de discerner les matériaux calcaires de différentes formations géologiques en fonction de leur proportion de silicium (Si), de calcium (Ca) ou de fer (Fe). Conjointement avec un calcul comparatif entre les indices de sphéricité de ces blocs, ils suggèrent leur captation dans les dépôts géologiques secondaires colluviaux de la faille de Ticul à vingt kilomètres du site.

Mots-clés: *Sihó, ressources géologiques secondaires, traces chimiques élémentaires, indices de sphéricité, stratégies de captation.*

Resumo

Estratégias para o aproveitamento de recursos líticos secundários no ambiente geológico do sítio pré-hispânico de Sihó (Yucatan) através da análise físico-química de instrumentos calcários

Sihó é um sítio arqueológico pré-hispânico localizado na Terra Baixa Maia do Norte da Península de Yucatán, onde tem sido documentado um número considerável de instrumentos de percussão e abrasão feitos de rochas calcárias, conhecido como manuports (Clark, 1988). Estes artefatos têm certas características físicas e químicas que podem ser sintomáticas de uma origem geológica particular. O tratamento estatístico dos datos extraídos pela fluorescência de raios X nos dá a possibilidade de discernir materiais calcários de diferentes formações geológicas, dependendo de sua proporção de silício (Si), cálcio (Ca) ou ferro (Fe). Juntamente com um cálculo comparativo entre os índices de esfericidade destas rochas, sugerem sua captação nos depósitos geológicos secundários coluvionares da falha do Ticul a vinte quilômetros do sítio.

Palavras-chave: *Sihó, recursos geológicos secundários, traços químicos elementares, índices de esfericidade, estratégias de captação.*

State of Play, Theoretical Framework and Research Objectives

The specialised archaeological bibliography on lithic industry and resource analysis, relevant to Mayan social formations, has mainly focused on the study of volcanic or metamorphic geological raw materials, often foreign, such as basalt, obsidian, flint or jade, etc. (Aoyama, 1993; Braswell y Glascock, 1998; Crabtree, 1968; Hirth, 2009; Moholy-Nagy, 2003; Pastrana, 1986; Shafer y Hester, 1991). The majority of the materials studied are lithics from primary geological deposits that have been mined by shaft or trench systems (Gallegos Gomora, 1994; Pastrana, 1986; Ruiz Aguilar, 1986; Titmus y Woods, 2002). Despite the lack of specialised articles from this area that highlight the economic and technological importance of artefacts made from secondary and local geological materials, such us hand hammers and polishers, scholars have analysed archaeological and ethnographic examples of these resources collection in pre-Hispanic, colonial and contemporary times, through direct community exploitation strategies (Ruiz Aguilar, 2007, 2019; Callejas Martínez, 2008; Clark, 1988; Águila Flores, 1993; Landa, 1556; Guzzy Arredondo y González Cruz, 1988; Hayden, 1987; Kidder, 1947; Madrid González, 2013; Mijangos Pantaleón, 2014; Morán Aragón, 2013; Proskouriakoff, 1962; Taladoire, 2016; Sheets y Gallardo, 2013; Taube et al., 2011).

Different types of primary or secondary geological deposits can be found in the surrounding environment, allowing for a diversity of exploitation strategies by human communities (Risch, 1995). At primary geological deposits, the rocks have suffered little erosion or movement processes due to natural phenomena. When mined, their extraction requires more specialised technology, resulting in more standardised materials. Another lithic resources extractive method, reported in numerous ethnographic and archaeological cases, is the exploitation of secondary geological deposits. These are deposits with fragmented and eroded materials, whose morphometry is transformed according to constant and prolonged natural phenomena, presenting physical and volumetric characteristics (sphericities) suitable for the tool function. The natural spherical shape of the selected cobbles adapts well to the hand and provides good technical manageability in relation to the task. A further consequence of naturally eroded rocks is the superficial decohesioned mineral elimination, which can hinder tool functionality. These geological characteristics facilitate the social lithic resource appropriation, given that secondary deposits are more easily exploited in terms of needed tools and working time.

Rocks were selected for the functional properties (manageability, durability, etc.) that apport to lithic tools, which in its case would confer value to other community works, such as obsidian or flint knapping. I agree with Risch (1995: 13) that "in absolute energy terms, inorganic resources do not increase the available social energy balance". This precept can be applied to a primary rock outcrop or a secondary geological deposit, subjected to raw materials extraction as work object. In such a way,

raw materials without labour will not increase this energy balance and will have to be subject to a previous transformation, also as an object of labour, developing in act and adopting its use value (Marx, 1975) in its technological capacity to generate surplus value.

> when the object on which the work is performed has already been (...) filtered by previous work, we term it raw material. Such is the case, for example, of copper removed from the vein to be washed. All raw material is work object, but not all work object is raw material. To this effect, it is necessary for it to undergo a degree of transformation by means of the work (Marx, 1975, p. 217).

This approach implies adopting the premise that traditional agricultural societies generally appropriate the natural resources with adequate material properties and in more accessible possible way, as a manifestation form of social relations production to obtain economic surplus. At the same time, it also entails dimensioning the production system in a dialectical sense, concretised in an economic practice such as raw lithic materials extraction from their natural sources with the use of means and work forces, within a particular social and historical context like de Maya.

Based on exposed theoretical assumptions, together with the complementary methodological use of X-ray fluorescence techniques and sphericity indexes calculus, the first objective of this article it's identify the potential source of limestone cobbles that were used as percussion and abrasion tools at Sihó. Moreover, with its development, it aims to assess the effectiveness of these techniques applied in their analytical approach to the archaeological and reference objects. Finally, with the physical and chemical data obtained, and using available historical chronicles and archaeological documentation, we will attempt to explain how the Mayans who inhabited the site, selected and exploited those geological resources, adding further to the existing bibliographic documentation.

Materials and Methods for Technical Analysis

The analysis of the ceramics from Sihó, associated with the archaeological sample, suggests a relative occupation chronology from the Middle to Terminal Classic Period (Jiménez *et al.*, 2006; Jiménez, 2007). However, the peak and maximum build-up of structures visible today would have been during the Late Classic, with a decline towards the Terminal (Fernández, 2010; Jiménez *et al.*, 2006; Jiménez, 2007; Pat Cruz, 2006).

The Sihó archaeological site sample analysed to obtain morphometric sphericity indices calculations, consists in 26 cobbles used as percussion or abrader tools (Figure 1A, B; Table 1). The geological reference sample analysed for the statistical contrast between sphericity indexes, consist of 179 natural stone cobbles sampled in the vicinity of Sihó and 32 in the Ticul fault. These last were selected from a total sample of 138 individual with a majority of 106 uneroded angular clast (Figure 1C, D; Table 2), that was used to calculated the proportions between angular or rounded morphologies.

For the chemical element tests were used seven archaeological specimens (Table 3) and 31 reference samples from the three main geological formations of the Yucatan Peninsula: Carrillo Puerto, Chichén Itzá and Icaiché (Table 4; Figure 2, 3) obtained during 2015 and 2017 field trips. These formations were chosen due to their locality or proximity to the Sihó site and because they contain calcareous materials that could be exploited due to their physical properties for abrading and percussion.

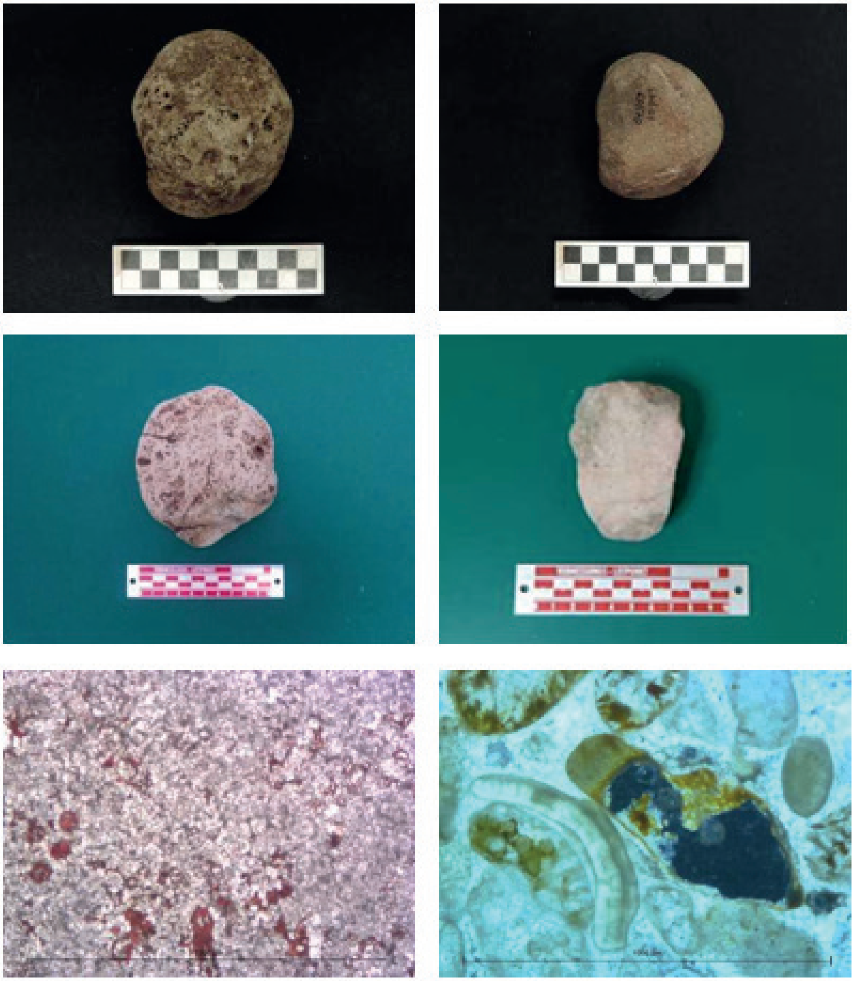


Figure 1. Sihó's archaeological cobbles: Crystalline dolomite, A (upper left) and grainstone/biocalcarenite, B (upper right). Natural cobbles from Ticul fault: Crystalline dolomite C (centre left) and grainstone/biocalcarenite D (centre right). Thin-section petrographs: Crystalline dolomite, E (down left, 5X) and grainstone/biocalcarenite from Ticul fault, F (down right, 20X). Note. Limestone classification based on their particle proportions (Embry & Klovan, 1971; modified from Dunham, 1962).

Table 1. Sihó archaeological cobbles

ID	*Lenght (L)*	*Widht (l)*	*Thickness (E)*	*π=(E:L)·100*	*Ai=(L+l):2E*
5	60,00	41,00	45,00	75,00	1,12
343	70,00	47,00	54,00	77,14	1,08
358	79,00	61,00	69,00	87,34	1,01
323	89,00	72,00	66,00	74,16	1,22
358	79,00	61,00	69,00	87,34	1,01
299	71,00	69,00	57,00	80,28	1,23
313	82,00	72,00	67,00	81,71	1,15
321	84,00	78,00	72,00	85,71	1,12
339	56,00	50,00	49,00	87,50	1,08
354	102,00	92,00	64,00	62,74	1,52
364	95,00	66,00	61,00	64,21	1,32
403	57,00	51,00	51,00	89,47	1,06
318	35,00	25,00	24,00	68,57	1,25
332	55,00	48,00	38,00	69,10	1,35
305	72,00	66,00	45,00	62,50	1,53
400	42,00	32,00	22,00	52,38	1,68
302	75,00	68,00	64,00	85,33	1,12
23	60,00	52,00	44,00	73,33	1,27
300	77,00	67,00	53,00	68,83	1,36
310	70,00	67,00	52,00	74,28	1,32
355	75,00	69,00	63,00	84,00	1,14
359	146,00	80,00	38,00	26,03	2,97
418	91,00	76,00	67,00	73,63	1,25
19	75,00	73,00	58,00	77,33	1,28
331	126,00	89,00	43,00	34,13	2,50
330	99,00	73,00	67,00	67,68	1,28

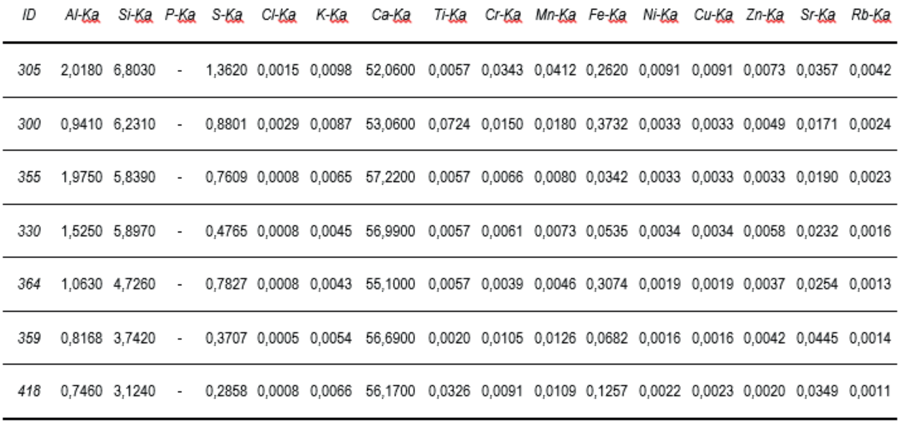
Note.: A bsolute sizes (mm), Cailleux (Ai) and Lütting (π) sphericity indexes

Table 2. Ticul natural cobbles.

ID	*Lenght (L)*	*Widht (l)*	*Thickness (E)*	*π=(E:L)·100*	*Ai=(L+l):2E*
R-1	70,00	57,00	39,00	55,71	1,63
R-2	124,00	67,00	45,00	35,43	2,12
R-3	84,00	75,00	55,00	65,48	1,45
R-4	106,00	72,00	52,00	49,06	1,71
R-5	147,00	139,00	50,00	34,01	2,86
R-6	68,00	66,00	58,00	85,29	1,16
R-7	84,00	63,00	47.00	55.95	1,56
R-8	75,00	62,00	51,00	68,00	1,34
R-9	55,00	46,00	40,00	72,73	1,26
R-10	66,00	65,00	35,00	53,03	1,87
R-11	97,00	66,00	38,00	39,18	2,14
R-12	50,00	40,00	34,00	68,00	1,32
R-13	48,00	44,00	28,00	58,33	1,64
R-14	100,00	68,00	41,00	41,00	2,05
R-15	53,00	50,00	38,00	71,70	1,36
R-16	52,00	43,00	37,00	71,15	1,28
R-17	96,00	87,00	33,00	34,37	2,77
R-18	126,00	81,00	48,00	38,10	2,16
R-19	130,00	65,00	51,00	39,23	1,91
R-20	95,00	85,00	28,00	29,47	3,21
R-21	65,00	38,00	30,00	46,15	1,72
R-22	114,00	87,00	44,00	38,60	2,28
R-23	33,00	28,00	20,00	60,60	1,52
R-24	46,00	33,00	18,00	39,13	2,19
R-25	42,00	41,00	28,00	66,67	1,48
R-26	80,00	73,00	55,00	62,50	1,39
R-27	37,00	31,00	25,00	67,57	1,36
R-28	116,00	78,00	43,00	37,07	2,26
R-29	112,00	75,00	23,00	20,54	4,06
R-30	46,00	36,00	33,00	71,74	1,24
R-31	48,00	33,00	29,00	60,42	1,40
R-32	130,00	114,00	84,00	64,62	1,45

Note. Absolute sizes (mm), Cailleux (Ai) and Lütting (π) sphericity indexes.

Table 3. Chemical element percentages of Sihó archaeological cobbles

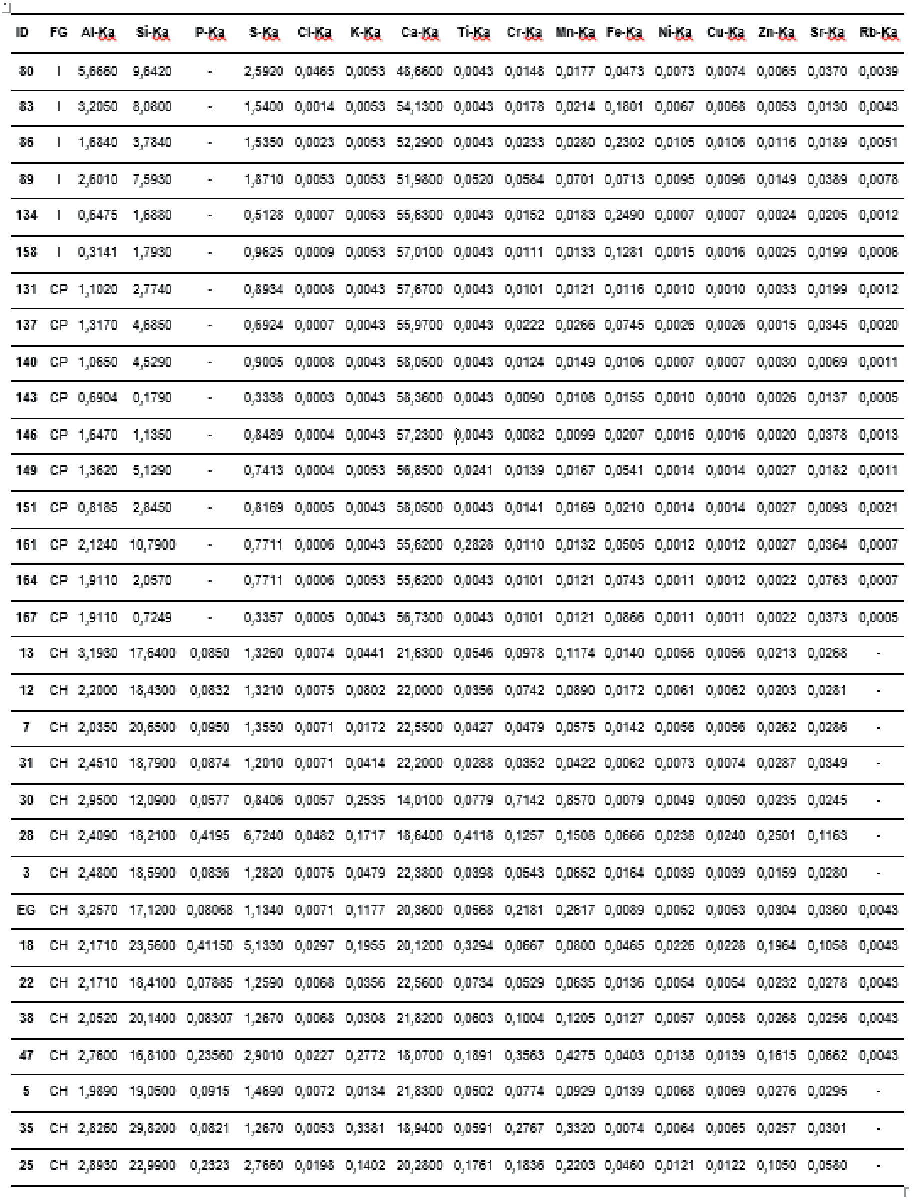


ID	*Al-Ka*	*Si-Ka*	*P-Ka*	*S-Ka*	*Cl-Ka*	*K-Ka*	*Ca-Ka*	*Ti-Ka*	*Cr-Ka*	*Mn-Ka*	*Fe-Ka*	*Ni-Ka*	*Cu-Ka*	*Zn-Ka*	*Sr-Ka*	*Rb-Ka*
305	2,0180	6,8030	-	1,3620	0,0015	0,0098	52,0600	0,0057	0,0343	0,0412	0,2620	0,0091	0,0091	0,0073	0,0357	0,0042
300	0,9410	6,2310	-	0,8801	0,0029	0,0087	53,0600	0,0724	0,0150	0,0180	0,3732	0,0033	0,0033	0,0049	0,0171	0,0024
355	1,9750	5,8390	-	0,7609	0,0008	0,0065	57,2200	0,0057	0,0066	0,0080	0,0342	0,0033	0,0033	0,0033	0,0190	0,0023
330	1,5250	5,8970	-	0,4765	0,0008	0,0045	56,9900	0,0057	0,0061	0,0073	0,0535	0,0034	0,0034	0,0058	0,0232	0,0016
364	1,0630	4,7260	-	0,7827	0,0008	0,0043	55,1000	0,0057	0,0039	0,0046	0,3074	0,0019	0,0019	0,0037	0,0254	0,0013
359	0,8168	3,7420	-	0,3707	0,0005	0,0054	56,6900	0,0020	0,0105	0,0126	0,0682	0,0016	0,0016	0,0042	0,0445	0,0014
418	0,7460	3,1240	-	0,2858	0,0008	0,0066	56,1700	0,0326	0,0091	0,0109	0,1257	0,0022	0,0023	0,0020	0,0349	0,0011

Note: Geological formations (FG), Carrillo Puerto (CP), Icaiché (I) and Chichén Itzá (CHI).

The lithic materials chemical quantification was carried out with the SANDRA X-Ray Fluorescence Spectroscopic Technique, developed by the Physics Institute of the National Autonomous University of Mexico. This technique detects the trace elements in the sample and their proportion in parts per million (ppm), and the resulting proportions have been converted to percentages for their statistical treatment. Like the calibration value was used the standard reference (SRM-NIST) of Portland 1880a and Montana 2711 cement. The analysis was done directly on lithic sample without pulverisation, through four scannings with different x-ray beam penetration angles. The median was statistically extrapolated from the obtained results to detect oversized inclusions of silica or other components to minimize possible distortions caused by extreme values. To process the archaeometric data was used the free software: Paleontological Statistics Software Package for Education and Data Analysis (PAST 3.20) (Hammer *et al*., 2001).

Table 4. Chemical element percentages of Ticul fault reference cobbles



ID	FG	Al-Ka	Si-Ka	P-Ka	S-Ka	Cl-Ka	K-Ka	Ca-Ka	Ti-Ka	Cr-Ka	Mn-Ka	Fe-Ka	Ni-Ka	Cu-Ka	Zn-Ka	Sr-Ka	Rb-Ka
80	I	5,6660	9,6420	-	2,5920	0,0465	0,0053	48,6600	0,0043	0,0148	0,0177	0,0473	0,0073	0,0074	0,0065	0,0370	0,0039
83	I	3,2050	8,0800	-	1,5400	0,0014	0,0053	54,1300	0,0043	0,0178	0,0214	0,1801	0,0067	0,0068	0,0053	0,0130	0,0043
86	I	1,6840	3,7840	-	1,5350	0,0023	0,0053	52,2900	0,0043	0,0233	0,0280	0,2302	0,0105	0,0106	0,0116	0,0189	0,0051
89	I	2,6010	7,5930	-	1,8710	0,0053	0,0053	51,9800	0,0520	0,0584	0,0701	0,0713	0,0095	0,0096	0,0149	0,0389	0,0078
134	I	0,6475	1,6880	-	0,5128	0,0007	0,0053	55,6300	0,0043	0,0152	0,0183	0,2490	0,0007	0,0007	0,0024	0,0205	0,0012
158	I	0,3141	1,7930	-	0,9625	0,0009	0,0053	57,0100	0,0043	0,0111	0,0133	0,1281	0,0015	0,0016	0,0025	0,0199	0,0006
131	CP	1,1020	2,7740	-	0,8934	0,0008	0,0043	57,6700	0,0043	0,0101	0,0121	0,0116	0,0010	0,0010	0,0033	0,0199	0,0012
137	CP	1,3170	4,6850	-	0,6924	0,0007	0,0043	55,9700	0,0043	0,0222	0,0266	0,0745	0,0026	0,0026	0,0015	0,0345	0,0020
140	CP	1,0650	4,5290	-	0,9005	0,0008	0,0043	58,0500	0,0043	0,0124	0,0149	0,0106	0,0007	0,0007	0,0030	0,0069	0,0011
143	CP	0,6904	0,1790	-	0,3338	0,0003	0,0043	58,3600	0,0043	0,0090	0,0108	0,0155	0,0010	0,0010	0,0026	0,0137	0,0005
146	CP	1,6470	1,1350	-	0,8489	0,0004	0,0043	57,2300	0,0043	0,0082	0,0099	0,0207	0,0016	0,0016	0,0020	0,0378	0,0013
149	CP	1,3620	5,1290	-	0,7413	0,0004	0,0053	56,8500	0,0241	0,0139	0,0167	0,0541	0,0014	0,0014	0,0027	0,0182	0,0011
151	CP	0,8185	2,8450	-	0,8169	0,0005	0,0043	58,0500	0,0043	0,0141	0,0169	0,0210	0,0014	0,0014	0,0027	0,0093	0,0021
161	CP	2,1240	10,7900	-	0,7711	0,0006	0,0043	55,6200	0,2828	0,0110	0,0132	0,0505	0,0012	0,0012	0,0027	0,0364	0,0007
164	CP	1,9110	2,0570	-	0,7711	0,0006	0,0053	55,6200	0,0043	0,0101	0,0121	0,0743	0,0011	0,0012	0,0022	0,0763	0,0007
167	CP	1,9110	0,7249	-	0,3357	0,0005	0,0043	56,7300	0,0043	0,0101	0,0121	0,0866	0,0011	0,0011	0,0022	0,0373	0,0005
13	CH	3,1930	17,6400	0,0850	1,3260	0,0074	0,0441	21,6300	0,0546	0,0978	0,1174	0,0140	0,0056	0,0056	0,0213	0,0268	-
12	CH	2,2000	18,4300	0,0832	1,3210	0,0075	0,0802	22,0000	0,0356	0,0742	0,0890	0,0172	0,0061	0,0062	0,0203	0,0281	-
7	CH	2,0350	20,6500	0,0950	1,3550	0,0071	0,0172	22,5500	0,0427	0,0479	0,0575	0,0142	0,0056	0,0056	0,0262	0,0286	-
31	CH	2,4510	18,7900	0,0874	1,2010	0,0071	0,0414	22,2000	0,0288	0,0352	0,0422	0,0062	0,0073	0,0074	0,0287	0,0349	-
30	CH	2,9500	12,0900	0,0577	0,8406	0,0057	0,2535	14,0100	0,0779	0,7142	0,8570	0,0079	0,0049	0,0050	0,0235	0,0245	-
28	CH	2,4090	18,2100	0,4195	6,7240	0,0482	0,1717	18,6400	0,4118	0,1257	0,1508	0,0666	0,0238	0,0240	0,2501	0,1163	-
3	CH	2,4800	18,5900	0,0836	1,2820	0,0075	0,0479	22,3800	0,0398	0,0543	0,0652	0,0164	0,0039	0,0039	0,0159	0,0280	-
EG	CH	3,2570	17,1200	0,08068	1,1340	0,0071	0,1177	20,3600	0,0568	0,2181	0,2617	0,0089	0,0052	0,0053	0,0304	0,0360	0,0043
18	CH	2,1710	23,5600	0,41150	5,1330	0,0297	0,1955	20,1200	0,3294	0,0667	0,0800	0,0465	0,0226	0,0228	0,1964	0,1058	0,0043
22	CH	2,1710	18,4100	0,07885	1,2590	0,0068	0,0356	22,5600	0,0734	0,0529	0,0635	0,0136	0,0054	0,0054	0,0232	0,0278	0,0043
38	CH	2,0520	20,1400	0,08307	1,2670	0,0068	0,0308	21,8200	0,0603	0,1004	0,1205	0,0127	0,0057	0,0058	0,0268	0,0256	0,0043
47	CH	2,7600	16,8100	0,23560	2,9010	0,0227	0,2772	18,0700	0,1891	0,3563	0,4275	0,0403	0,0138	0,0139	0,1615	0,0662	0,0043
5	CH	1,9890	19,0500	0,0915	1,4690	0,0072	0,0134	21,8300	0,0502	0,0774	0,0929	0,0139	0,0068	0,0069	0,0276	0,0295	-
35	CH	2,8260	29,8200	0,0821	1,2670	0,0053	0,3381	18,9400	0,0591	0,2767	0,3320	0,0074	0,0064	0,0065	0,0257	0,0301	-
25	CH	2,8930	22,9900	0,2323	2,7660	0,0198	0,1402	20,2800	0,1761	0,1836	0,2203	0,0460	0,0121	0,0122	0,1050	0,0580	-

Note. Geological formations (FG), Carrillo Puerto (CP), Icaiché (I) and Chichén Itzá (CHI).

Siho Site Geological Setting and Reference Sample Location

Sihó (15Q YN950681, Garza y Kurjack, 1980) sits on the Carrillo Puerto geological formation that occupies the northern, northwestern and eastern areas of the Yucatan Peninsula, partially surrounding the Chichén Itzá formation from east to west and north to south (Duch, 1988) (Figure 2, 3). The site is located approximately 20 kilometres southeast of the closest point of the Chichén Itzá formation, which extends into the southern and northern half of the Yucatan Peninsula and coincides with the most extreme western boundary of the Ticul fault (Figure 4C). This fault is associated with the Icaiché formation outcrops, underlying the Chichén Itzá formation, and runs south-southwest across the north of the Yucatán Peninsula (Figure 2, 3). We are dealing with a geological formation in a fault context, affected by differential diaparism processes, with outcrops of older geological formations rising above the modern Middle and Upper Eocene Chichén Itzá geological formation strata. These processes are related to the tectonic uplift of less dense and plastic rocks, through more dense and recent overlying ones (Marín *et al*., 2004).

The Yucatán Peninsula calcareous soils were generated along the Upper Cretaceous (100.5-66.0 Ma) (Cohen *et al*., 2013),[1] Paleogene (66.0-23.03 Ma) and Neogene (23.03-2.58 Ma), being dominant the Eocene (56,0-33,9 Ma), Oligocene (33,9-23,03 Ma), Miocene (23.03-5.333 Ma) and Pliocene (5.333-2.58 Ma) formations (Dutch, 1988; Flores, 1974). Cretaceous and Paleogene surface materials have a high hardness, compared to more modern Neogene materials (Duch, 1988). During the Pleistocene, the calcareous rock fragments (caliche), more or less eroded, which covers a large part of the emerging Cretaceous, Eocene, Oligocene, Miocene and Pliocene strata, was formed (López Ramos, 1977). This superficial alteration, as well as the development of the peninsular coast, would continue throughout the Holocene.

Geological reference samples were collected at different outcrops and secondary deposits by field prospecting surveys, to obtain a minimum representative sample of lithological contexts that characterise the main Yucatan Peninsula formations (Carrillo Puerto, Chichén Itzá and Icaiché) (Figure 3), described below. The geological reference sample used for the elemental analyses includes a total of 31 prospected examples from the indicated contexts. The morphometric data sampling system used for sphericity indexes comparison is an adaptation of Howard's Area Method (1993) to the characteristics of our colluvial geological context. The system is based on a total collection of 138 (>100) natural cobbles, that do not exceed

---

[1] Applies to all geological chronologies listed in the text.

the maximum size of any archaeological cobble within a square of one m^2 (Figure 4B). This experimental sampling was done on the occidental north face of the Ticul fault, where the geological sample was collected too for its chemical analysis. As a morphometric analytical contrast, we follow the same method with a collection of 177 reference cobbles at Sihó archaeological site.

3.1. Icaiché Formation

The Icaiché formation began to form during the Upper Cretaceous Maastrichtian (72.1 ±2 - 66.0 Ma), from the transition level (undifferentiated) towards the Palaeogene (66.0 - 23.03 Ma), although it fully developed during the Palaeocene (66.0-56.0 Ma) and Lower Eocene (56.0-47.8 Ma) (López Ramos, 1977). We are dealing with a geological formation in a fault context, affected by differential diaparism processes (Marín *et al*., 2004), with outcrops of older formations rising above the modern Middle and Upper Eocene Chichén Itzá geological formation strata. These processes are related to the tectonic uplift of less dense and plastic rocks, through more dense and recent overlying ones (Marín *et al*., 2004).

The Upper Cretaceous formations are mainly composed of translucent anhydrite rocks, with intercalated crystalline dolomitic limestone bodies (López Ramos, 1977). Furthermore, these formations contain fine to medium sized cryptocrystalline calcareous intercalations, microfossils, oolites and pseudolites, forming calcarenite (López Ramos, 1977). These rocks are reported as Upper Cretaceous Peten-type limestones (Aguilar Nogales, 1979a, 1979b; López Ramos, 1977; Miranda Huerta, 2005; Virgen Magaña y Baca Carreón, 1988). This description of materials coincides with samples (Figure 3A, 3B) collected in the Ticul fault, which we classify as crystalline dolomite and grainstone -limestone classification based on depositional texture and particle proportions (Embry & Klovan, 1971; modified from Dunham, 1962)-, this last according to their well-cemented, punctually silicified and/or dolomitized depositional texture, with eroded contents of calcareous particles, fossils and oolites (Sánchez Rojas y Zamorano Montiel, 1993).The Paleocene rocks (66.0 - 56.0 Ma) are described as compact, fine-grained, white to light grey limestones with abundant microfossils, intercalated between marls (Duch, 1988; García Gil y Graniel Castro, 2010; López Ramos, 1977). The Lower Eocene rocks (56.6 - 47.8 Ma), also pertaining to the Icaiché geological formation, hardly lithologically differ to the other Eocene materials, a situation which complicates their phase division (López Ramos, 1977). Basically, they are compact microcrystalline limestones, of a white and cream to light grey colour, with microfossils (foraminifera) and intercalated marls and shales (Butterlin y Bonet, 1960; Duch, 1988; García Gil y Graniel Castro, 2010); López Ramos, 1977).

3.2. Chichén Itzá Formation

The Chichén Itzá formation (Piste member) encompasses Middle Eocene (47.8-41.3 Ma) to Upper Eocene (41.3 Ma-33.9 Ma) strata (Butterlin y Bonet, 1960; García Gil y Graniel Castro, 2010; López Ramos, 1977). In these levels, lithologically similar to the Lower Eocene, there are reports of partially crystalline, compact, fine-grained, off-white to light grey limestones, with microfossils and intercalated with marls and crumbly shales (Duch, 1988; García Gil y Graniel Castro, 2010; López Ramos, 1977). Microfauna documented in the Chichen Itzá formation outcrops mainly correspond to Middle Eocene, mostly algae and foraminifera fossils (Butterlin y Bonet, 1960). Dolomitisation or silification degree of these geological materials is related to a reduction of macro-fossils, by a process of substitution of calcite by magnesium or silica in the contents of bioclasts and cementing agents (Álvarez Jr., 1954; Bustillo *et al.*, 2012; Duch, 1988; Henao Aristizábal y Martínez Casas, 2009; Tucker 1991). This process occurs depending on diagenetic conditions under which the geological formation was exposed during the sedimentation phases.

Soundings performed in Yucatán Peninsula's north-central zone (Bautista *et al.*, 2015; López Ramos, 1977), at Upper Eocene levels attached to Chumbec member, pertaining to Chichén Itzá formation according to García y Graniel (2010), show a recurrence of micritic[2] limestones, calcarenites, marls and shales.

3.3. Oligocene and Lower Miocene levels exceptionality

According to López Ramos (1977), García Gil y Graniel Castro (2010) and Miranda Huerta (2005), the Lower Oligocene (33.9-27.82 Ma) geological materials are not very visible on the surface. However, Upper Oligocene outcrops levels emerge (27.82-23.03 Ma) (López Ramos, 1977).) with the presence of stratified banks of bivalve molluscs, known as "conchuela." Basically, it is a cream and white limestone, powdery and coquinoid, with abundant mollusc and bryozoan fossils. Those materials levels are very similar to Lower Miocene (23.03-13.82 Ma) materials, documented at south of Mérida (García Gil y Graniel Castro, 2010; López Ramos, 1977). Mostly are outcrops of cream and white limestone and calcarenite, coquinoid, low cohesioned and partly conglomerate (Bautista Zuñiga *et al.*, 2004; Bautista *et al.*, 2015; López Ramos, 1977; Miranda Huerta, 2005).

3.4. Carrillo Puerto Formation

The Carrillo Puerto formation properly starts (Duch, 1988, 1991; García Gil y Graniel Castro, 2010) from the Upper Miocene (13.82-5.333 Ma) and Pliocene

---

[2] Carbonated matricial sediment composed by crystals less than 5 μm diameter.

(5.333 - 2.58 Ma), containing reddish to yellowish, clayey and hard limestones, soft and white coquinoid limestones and other more superficial white, hard and massive limestone levels (Duch, 1988). These geological levels contain gastrops, pelecypods, shells, ostrocodes and algae fossils (Bautista Zuñiga et al., 2004; Bautista et al., 2015; Cardoso Vázquez et al., 2004; López Ramos, 1977; Miranda Huerta, 2005), peloids and some sporadic ooids.

The Carrillo Puerto formation properly starts (Duch, 1988, 1991; García Gil y Graniel Castro, 2010) from the Upper Miocene (13.82 - 5.333 Ma) and Pliocene (5.333 - 2.58 Ma), containing reddish to yellowish, clayey and hard limestones, soft and white coquinoid limestones and other more superficial white, hard and massive limestone levels (Duch, 1988). These geological levels contain gastrops, pelecypods, shells, ostrocodes and algae fossils (Bautista Zuñiga et al., 2004; Bautista et al., 2015; Cardoso Vázquez et al., 2004; López Ramos, 1977; Miranda Huerta, 2005), peloids and some sporadic ooids.

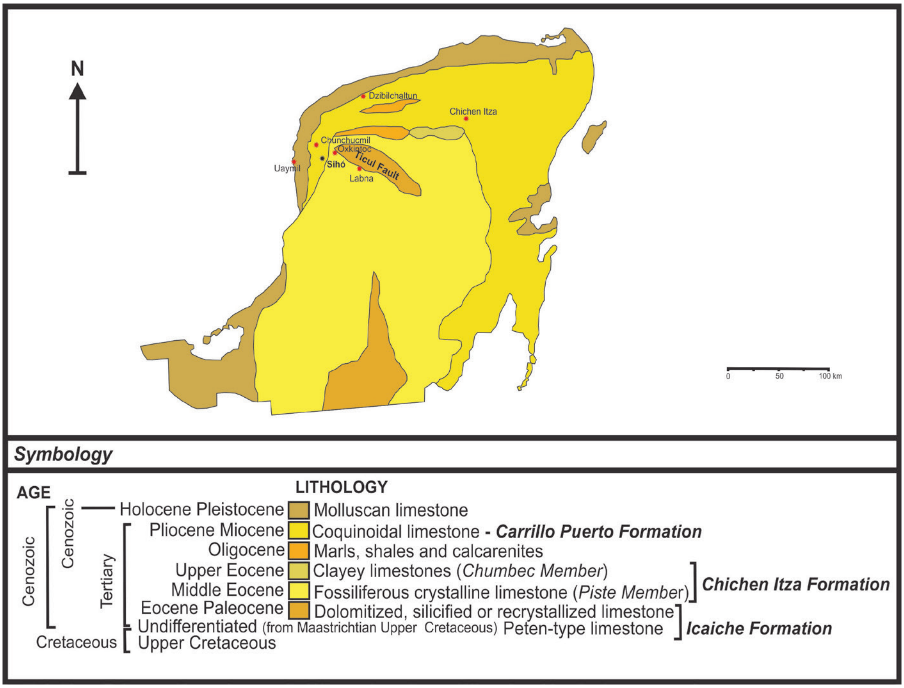


Figure 2. Yucatán Peninsula geomorphology and Sihó site geographic location. Modified from García and Graniel (2010). Located ancient sites contemporary with Sihó.

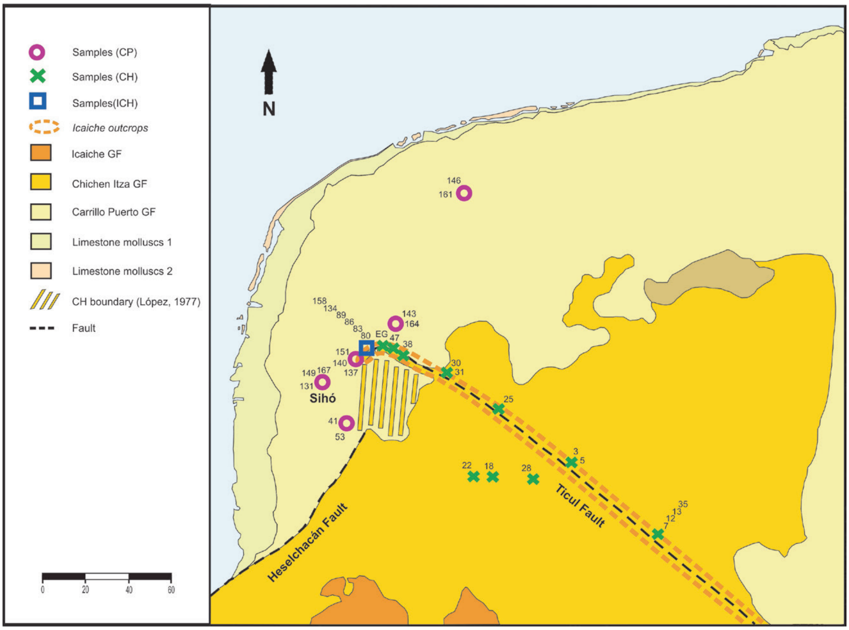


Figure 3. Geological reference sampling point locations. Note. Only includes the numeration of X-ray fluorescence chemically analysed samples. CP (Carrillo Puerto), ICH (Icaiché) and CHI (Chichén Itzá). Modified from the Geological-Mining Chart, Mexican Geological Service INEGI (2007) (Scale 1: 500,000).

Physical Characterisation of Siho's Secondary Geological Resources

In the Ticul fault rocky slopes (Figure 4) there are colluvial deposits which provide a large quantity of limestone materials fragmented by meteorization (temperature, water action and vegetation), with variable levels of surface erosion caused by the rainwater stationary circulation along the slopes. The most recent, less exposed, and rolled materials can present various edges and flat faces. Those older deposited materials, with more time exposed to the elements, present a major degree of roundness in their faces. However, this rounding or flattening is not homogenous due to the irregular action of rainwater and the limited extension of the Ticul fault slopes, which do not permit an easy rolling of the lithic materials. For these reasons these materials do not have homogeneous smooth surfaces, containing cavities and bumps (Figure 1C, D), unlike those coming from river or sea beds.

Figure 4. Areas, section and location of Howard’s (1993) sampling. (A) Upper left: geological sampling general area. (B) Upper right: geological sampling area detail. (C) Lower left: birds-eye view of western end Ticul fault. (D) Lower right: Ticul fault profile and maximum height from sampling point.

In geomorphology have been developed calculation methods to quantify the secondary lithic materials sphericity or flattening caused by natural phenomena action. Can be applied the Cailleux formula: $Ai = (L + l): 2E$ or that of Lütting: $\pi = E : L - 100$, being both inversely correlated (Cailleaux, 1951; Delgado Raack, 2008; Lütting, 1956; Risch, 1995). In Cailleux's index the values increase in relation to the sphericity decrease and in Lütting's index they increase in relation to the sphericity increase (Delgado Raack, 2008). The Cailleaux index considers the three dimensions of the object and better expresses the natural erosion on the rocks, unlike the Lütting index which only takes into account two dimensions. Cailleaux (1951) provided us some estimates linked to different natural cobbles formation processes: $Ai = 1.7\text{-}2$ (glacial), $Ai = 2.3\text{-}2.8$ (marine beaches), $Ai = 2.5\text{-}3.5$ (fluvial), although those calculations have not yet been applied to colluvial phenomena such as in the present case.

First was used the Howard (1993) sampling system to collect geological specimens and then the proportion between angular and rounded materials was established, given that is a deposit type formed by irregular natural erosion. The sphericity index of rounded materials was calculated using the Cailleaux formula (1951), in order to extract averages that typify a determinated secondary geological deposit, comparable with archaeological cobbles or with materials of other geological deposits (Table 1, 2; Figure 5). The morphological characterisation of Ticul fault slope sampled clast, assumes the proportionality among individuals showing sharp-edged faces and those with eroded or rounded surfaces. The angular rocks appear in a percentage of 77 %, while the rounded do so in 23 %, reflecting a slower erosion of the rocks compared to the outcrops fracture process.

To obtain alternative contrasting data that would allow to discard geological resource catchment areas that did not conform to the morphometries of our archaeological cobbles, was done a second natural cobbles sampling in a flat area among Sihó archaeological mounds. The Cailleaux sphericity index (Ai) arithmetic means of these geological materials results in 2.26, which is more adjusted for maritime deposits with higher grade of clast flattening. The geomorphological characteristics of these floodplains substantially differ to the Ticul fault colluvium environments, which have sufficient slope with higher water circulation and clast movement, resulting in their increased rounding degree. Regarding the Ticul fault geological reference sample (Table 5), the value average using an armonical mean [3] has results in Ai = 1.70. Therefore, it was considered that a ratio between Ai ⩽ 1.70 would be appropriate to discern materials from colluvial formations, considering the less regular natural processes that generate these geological deposits.

The average value of the Cailleaux index of the archaeological boulders (Ai = 1.27), fits within the average parameters expected for colluvial deposits. Is observed that such archaeological average is distant to that of the Sihó site geological reference sample and is closer to the Ticul sample average (Table 5). On the one hand, the sphericity index variability of the archaeological cobbles is low considering their variation coefficient and the standard deviation below mean. On the other, the variability between the archaeological and the Ticul reference sample are closer, compared with the Sihó reference sample, given their variation coefficients and the average proximity (Table 5).

Variance analysis among sphericity indices by means of Tukey's matrix (Table 5) gives a higher p-value than five % (0.05) in the relation between archaeological and the natural Ticul fault cobbles, indicating a possible affiliation to the same population due the means equality. For the natural rocks collected at Sihó, the relation probability is practically non-existent.

---

[3] More appropriate for increasing or decreasing trends as with sphericity indices, than the arithmetic mean.

Table 5. Descriptive statistical summary and population variance significance analysis between archaeological and natural cobbles Cailleaux index from Sihó and Ticul

Ai	*CAR arq/SH*	*CAR geo/SH*	*CAR geo/TC*
N	26	177	32
Media	1.35	2.26	1.85
Dev. stand	0.44	0.90	0.65
Coef. Var	32.65	39.85	35.17
Tukey's matrix	*CAR arq/SH*	*CAR geo/SH*	*CAR geo/TC*
CAR arq/SH		1.49E-06	0.065
CAR geo/SH	7.316		0.029
CAR geo/TC	3.180	3.629	

The contrasting graph between archaeological sample sphericity indexes and those of Ticul reference sample, shows an approximate interval (1-1.5 Ai / 60-90 π) that implies high sphericity degrees (Figure 5), hence the difference expressed by the low linear correlation between both samples (Table 6) could be caused by the social criteria selection of certain cobbles morphometries.

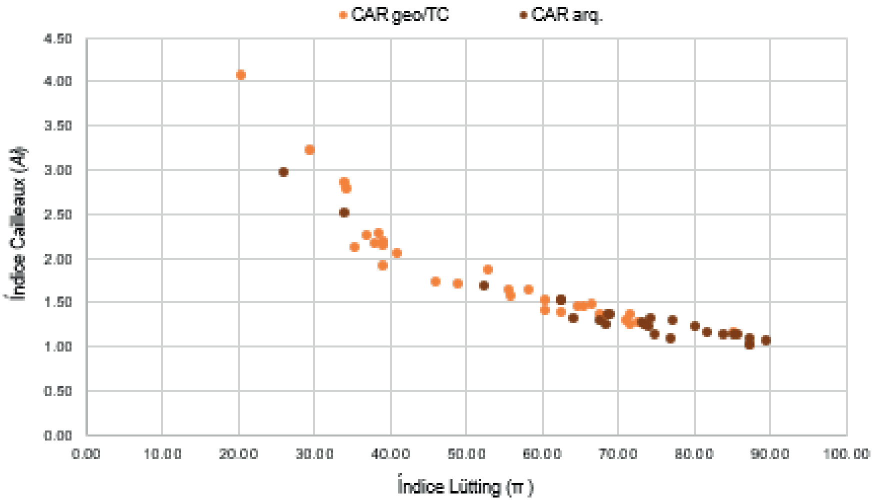


Figure 5. Graphic correlation between geological and archaeological sphericity indexes of Ticul fault and Sihó cobbles.

Table 6. Lineal correlation between geological and archaeological sphericity indexes of Ticul fault and Sihó cobbles.

Spearman's rs	*CAR arq/SH*	*CAR geo/TC*
CAR arq/SH	1	
CAR geo/TC	0.118	1

Elementary Identification of Sihó Secondary Geological Resources

X-ray fluorescence technique (XRF) was used to identify the different elemental contents in archaeological and geological reference samples (Table 3, 4). In both samples, the chemical elements diagnosed are silicon (Si), calcium (Ca), aluminium (Al), iron (Fe) and (Cu), nickel (Ni), rubidium (Rb), chlorine (Cl), potassium (K), phosphorus (P) and strontium (Sr). For principal component distribution (Figure 6) and statistics significance analyses (Table 7, 8), were select silica and calcium considering their higher variance, which may be related to a substitution process of calcite by silica into cements and bio-inclusions. (Álvarez, 1954; Bustillo et al., 2012; Duch, 1988; Tucker, 1991). However, after to do repeated tests among the geological reference sample, we observed that the silicon or calcium relation whit the rest chemical element diagnostiqued, which by containing a near zero variance, did not generate a significant distortion in the Principal Component test values distribution. For this reason, the iron element was introduced to provide a higher significance to the variance and Principal Component analyses applied in the lithic sampling tests. Likewise, another observed aspect regarding the variable iron proportion, among individuals of the lithic sample, is that it can be used to distinguish some geological formation with major contents of this chemical element.

Table 7. Elemental variability analysis on the geological sample

	Si-Ka	*Ca-Ka*	*Fe-Ka*
N	31	31	31
Variance	72.66	324.42	0.00

According to the Principal Components graph (Figure 6), the population that stands out most for its greater concentration and separation from the rest, is the sample from the Chichén Itzá formation collected in the south-southeast of the Ticul range from Maxcanú, Calkiní, Labná, Sayil and Oxkintok. The second reference population to be highlighted comes from Carrillo

Puerto geological formation, from Sihó, Kopomá and Dzityá locations. The last observable population, with more dispersed individuals, belongs to the northern face Ticul fault rocks. The wider dispersion of values may be due to the diaparism phenomenon involving the Icaiché and Chichén Itzá members, which is formed by different stratigraphic levels of calcareous materials with chemical

quantitative variability. At the same time, the Principal Components graph (Figure 6) illustrates a relatively higher correspondence of elemental concentration of archaeological items, with the distribution of values linked with the sample from the northern slope Ticul fault. Nevertheless, this exclusive relationship is questionable considering the positive probabilistic value above five % (0.05) with the calcium and silicon (Table 9), also present in the Carrillo Puerto geological formation reference sample, which is characterised by the apparent closeness of certain values to the archaeological sample ones (Figure 6).

The distribution in the principal components graph (Figure 6) among Chichén Itzá formation sampled individuals not allows us determinate a population homogeneous trend, due the distance in appearance frequency of its calcium and iron values, given its normal probability distribution is significantly less than 5 % (0.05) (Table 8). In this case, the population can only be established to a limited extent considering silicon independently on basis its probabilistic value adjusted to 5% (0.05), while the other formations have higher probability values for all three elements (Table 8). Consequently, the variance ratio between individuals from the archaeological sample and those from the Chichén Itzá formation, compared to the others, gives us a higher probability of association with the Icaiché first, followed by Carrillo Puerto.

One aspect to note in the Tukey matrix statistical application associated to the variance analysis (Table 9), is the negative relationship lower than five % (0.05) p-value, with the silicon and calcium elements, between the Carrillo Puerto geological formation reference samples and the Chichén Itzá formation. In contrast, with iron (table 9), this population relationship between samples is positive, having a higher p-value than five % (0.05), which indicates a proportional similarity with this particular element. However, the opposite occurs in the relationship with the Icaiché and Chichén Itzá geological formations materials, and Icaiché with Carrillo Puerto ones, with a probability lower than five % (0.05).

The Tukey matrix p-values in the case of silicon (Table 9), reveal the strongest relationship between the archaeological samples and those from the north face Ticul fault associated with Icaiché geological formation (I), closely followed by the Carrillo Puerto formation sample (CP). Also, the probabilistic

Table 8. Silicon, calcium and iron population variance significance analysis between the geological reference sample and the archaeological cobbles one. Archaeological cobbles (ARQ), Carrillo Puerto (CP), Icaiché (I) and Chichén Itzá (CHI)

Tukey matrix (Si)	*I*	*CP*	*CH*	*ARQ*
I		0.6665	1,54E-06	0.9992
CP	16.150		6,73E-10	0.7205
CH	124.800	168.100		2,77E-07
ARQ	0.1814	14.880	133.900	
Tukey matrix (Ca)	*I*	*CP*	*CH*	*ARQ*
I		0.0092	0.0000	0.3277
CP	47.940		0.0000	0.3885
CH	45.030	59.350		0.0000
ARQ	24.370	22.720	504.900	
Tukey matrix (Fe)	*I*	*CP*	*CH*	*ARQ*
I		0.0202	0.0024	0.9229
CP	43.580		0.8931	0.0021
CH	55.050	10.020		0.0001
ARQ	0.8859	55.670	68.870	

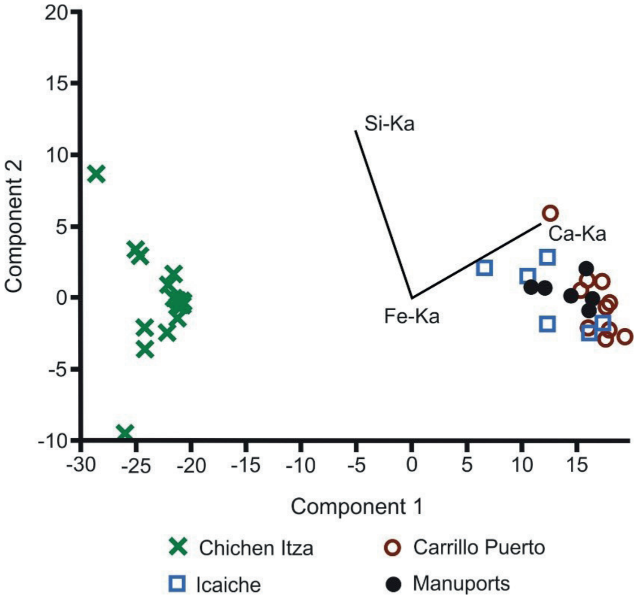
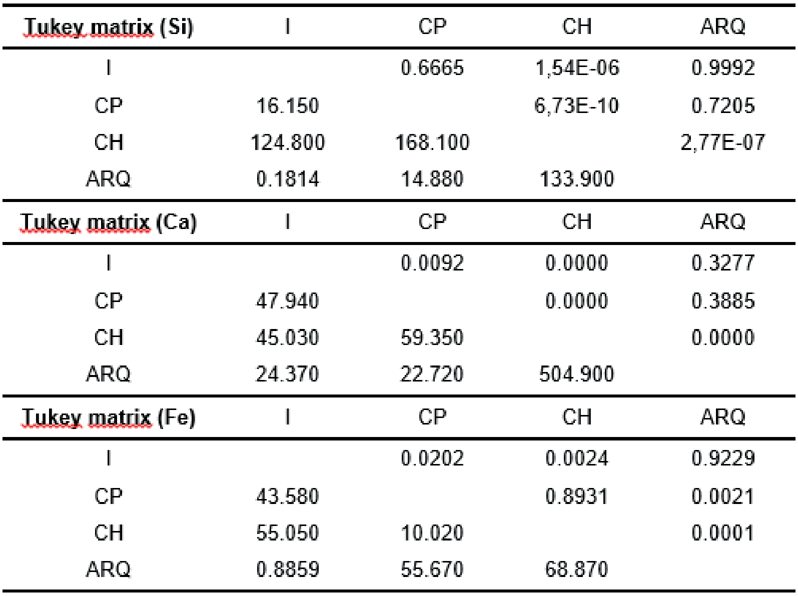


Figure 6. Elementary principal component analysis between the archaeological and the geological reference sample.

population relationship between the archaeological and Chichen Itzá formation (CH) sample doesn't comply as the probability value is inferior to five % (0.05). If analyse calcium (Table 9), can observe an elementary similarity of the archaeological sample with the reference ones gathered at Icaiché and Carrillo Puerto geological formations. Unlike silicon, the association with Carrillo Puerto samples is somewhat stronger. Also, in the case of silicon, the population relationship between archaeological and Chichén Itza reference samples isn't given with a p-value under five % (0.05) (Table 9). The Iron population values show a positive relationship probability above five % (0.05) of archaeological sample with that from the Icaiché geological formation. Regarding the other geological reference samples, the relationship probability fails with a lower p-value than five % (0.05) (Table 9).

To conclude, in the Tukey matrix are observed a relatively inverse relation between silicon and calcium (Table 9), although not proportional, among archaeological cobbles p-values with those from Icaiché and Carrillo Puerto geological formation reference samples. This inverse relationship, which also occurs between Carrillo Puerto and Chichén Itzá samples, may be due to the mentioned calcite substitution process by silica.

Table 9. Silicon, calcium and iron population variance significance analysis between the geological reference sample and the archaeological cobbles one. Archaeological cobbles (ARQ), Carrillo Puerto (CP), Icaiché (I) and Chichén Itzá (CHI)



Tukey matrix (Si)	I	CP	CH	ARQ
I		0.6665	1,54E-06	0.9992
CP	16.150		6,73E-10	0.7205
CH	124.800	168.100		2,77E-07
ARQ	0.1814	14.880	133.900	

Tukey matrix (Ca)	I	CP	CH	ARQ
I		0.0092	0.0000	0.3277
CP	47.940		0.0000	0.3885
CH	45.030	59.350		0.0000
ARQ	24.370	22.720	504.900	

Tukey matrix (Fe)	I	CP	CH	ARQ
I		0.0202	0.0024	0.9229
CP	43.580		0.8931	0.0021
CH	55.050	10.020		0.0001
ARQ	0.8859	55.670	68.870	

Some Notes about the Social Lithic Production Organisation at Siho

The statistical treatment of data provided by both archaeometric techniques (XRF and sphericity index) and their contrast, strengthens our argument that the Maya of Sihó were selecting these calcareous materials. Such a selection was probably based on certain cobbles morphometries that provided manageability to the grinding hand tools, as well as for their durability or abrasive capacity. Most of these materials were not collected in immediate surroundings of the Sihó site, due to their scarcity, and it's probable that they were collected from more distant geological sources, perhaps from

the Ticul fault. The cobbles appropriation strategies focused in part on the exploitation of secondary geological deposits, formed mainly during the Pleistocene (López Ramos, 1977), although these materials have as their primary geological source the underlying Cretaceous and Palaeogene Icaiché formation outcrops, in particular the Upper Cretaceous Maastrichtian, Palaeocene and Lower Eocene ones.

The Cretaceous and Palaeogene surface rocks are harder than those of the Neogene (Duch, 1988), which gives greater strength and functional durability to the instruments. Another element to consider is the lithological relationship between the Upper Cretaceous limestones (Aguilar, 1979a, 1979b; López, 1977; Miranda, 2005; Virgen and Baca, 1988), located in outcrops and secondary geological deposits of the Ticul fault, with several archaeological boulders from Sihó. The homogeneity in the arrangement, morphology, particle size and high cohesion of particles in the Icaiché Formation grainstones and crystallines rocks (Figure 3), provide a good abrasive property and durability to the artefacts (Pujol, 2022), probably valued in economic terms by the Late and Terminal Classic Maya settled at Sihó.

A straight line of approximately twenty km runs from the Sihó site to the nearest foothills in Ticul. This spatial range corresponds well with the second concentric area (home range) according to Pètrequin & Jeunesse (1995) and De Grooth (1994) site catchment model (Figure 7), and those suggested for French or Rhenish Neolithic geological resource catchment distances. These researchers have proposed concentric spatial ratios of material exploitation, among the contexts where the transformation and the use of artefacts occur. The first interval involves an area up to about ten km from the site (site territory), which can be covered on foot in approximately two hours. This hypothetical range would be part of the territory directly linked to the site and adds its immediate areas. A second zone of action covers a distance of ten to thirty km and can be shared by several settlements (home range). These distances can be reached in journeys of six to eight hours. In our case, the topography is flat and can be walked in four or five hours, if not faster, to access the lithic sources.

The secondary geological deposited materials accessibility is high, due to the inherent sediment characteristics without a compact matrix substrate, making it easily removable. In addition, it is a physical context with no difficulty of access from the site of Sihó, that does not imply any kind of spatial adaptation or infrastructural arrangement. The visibility that allows vegetation to grow varies according to the season, but clearing is easy with the means available in Prehispanic times, such as stone and wooden tools (Figure 4).

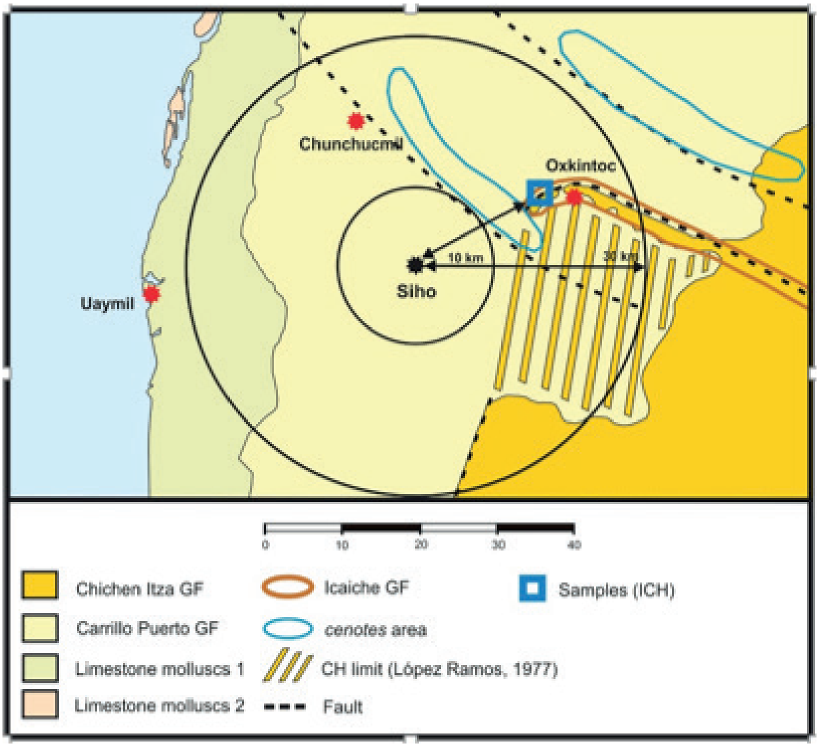


Figure 7. Raw material catchment concentric model. Adaptation to the model developed by De Grooth (1994) and Pétrequin & Jeunesse (1995). Modified from the Geological-Mining Chart (Servicio Geológico Mexicano, 2007). Located ancient sites contemporary with Sihó..

At several other Southeast Mayan archaeological sites, has been reported evidence of secondary geological resource exploitation. They provide spatio-temporal working ratios to those proposed for Sihó, but in different geological spaces. At archaeological sites of La Libertad (Clark, 1988), Chiapa de Corzo

(Guzzy Arredondo y González Cruz, 1988; Ruiz Aguilar, 2019) and Chinkultic (Ruiz Aguilar, 2007), located in the Chiapas Maya Highlands, the procurement of fluvial boulders to be used as grinding, abrasive and percussion tools, was a recurrent practice between the Preclassic and the Late Classic. Particularly, at the Early Classic Chiapa de Corzo site, the quartzite is the constituting raw material for most of the boulders recorded (Guzzy Arredondo y González Cruz, 1988). By side, the majority of the grinding artefacts at the Preclassic – Late Classic Chinkultic archaeological contexts (Ruiz Aguilar, 2007), are made with volcanic tuff and sandstone boulders. In the case of La Libertad Preclassic archaeological site, most reported cobbles tools are made of quartzite, granite and sandstone (Clark, 1988). Such geological materials could be obtained in secondary deposits from the main Sierra Madre and Chiapas Highlands rivers: the Grijalva, the Chiquito, the Nandalumi or the Santo Domingo, and their local tributaries closest to the sites (González Cruz y Cuevas García,1990). These riverbeds are located at a maximum distance of forty km from archaeological centers, with the furthest being Chinkultic, and less than twenty km La Libertad or Chiapa de Corzo sites. In Joya de Cerén, a site with Middle Classic to Postclassic chronologies, located in the Salvador Maya Highlands, at the Zapotitan valley, there are evidence of lithic debitage with fluvial boulder cortex remains. There have also been reports some percussion and abrasive tools, made with cobbles collected from a water course at ten km from the site (Sheets y Gallardo, 2013), possibly the Sucio river or a tributary.

In Uaxactún, located in the Southern Maya Lowlands, are registered (Kidder, 1947; Ruiz Aguilar, 2019) the use of limestone or granite river cobbles as polishers, from the Middle-Late Preclassic to the Terminal Classic. Kidder (1947) also reports flint and limestone cobbles, collected in the surroundings of the same site, used as hammers. According to Moholy-Nagy (2003), cobbles were carried from the Peten Itza lake, some thirty km away from Uaxactún. Mijangos Pantaleón (2014), also reports in Salinas de los Nueve Cerros (Guatemala), with a chronology from the Middle Preclassic to the Late Classic period, the use of natural cobbles to make manos and apodic metates. The lithic raw materials used probably were from nearby rivers, less than five km away, such as the Negro or Chixoy at Sacapulas, or the Cuilco and Pucal at Huehuetenango. Toniná is a site with Late Preclassic to Late Postclassic chronologies, located in the valley of Ocosingo in Chiapas, where Taladoire (2016) notes the use of volcanic (basalt) or metamorphic (diorite, serpentine, jadeite) cobbles to make bifacial artefacts. These rocks were collected in the nearby rivers descending from the highlands, like the Jatate and its main tributaries, the Chantechac and La Virgen, at about 5 km from the archaeological site.

Likewise, in the Southern Lowlands archaeological site of Huijo, from the Classic Period, located on the course of the Huijo river, a tributary of the

Motagua (Guatemala), researchers (Callejas Martínez, 2008) have documented large quantities of pyroclastic obsidian nodule fragments collected in a riverbed less than five km away. At Classic sites of Las Pilas or La Oscurana (Pueblo Nuevo, Municipality of Usumatlan, Zacapa), situated on The Palmilla's east shore, other affluent of the Motagua river, Callejas Martínez (2008) also report jade and serpentine cobbles gathering and processing. In El Tambor upper course river, another Motagua tributary, has been documented the presence of workshops with jade debris, associated to Late Classic ceramic (Taube et al., 2011). For this area, Taube et al. (2011) propose two different ways to resources direct extraction: the surface collection of cobbles from the alluvial and fluvial basins, and/or the jade clast extraction from the same basins' eroded outcrops.

One could suspect a possible economic link between the collection of these calcareous resources and the flint or chalcedony extraction in the same geological contexts. López Ramos (1977) report siliceous rocks in the Paleocene and Lower Eocene calcareous outcrops of Ticul range, and its extraction also would possible with a use of percussion tools made with hard calcareous cobbles. For example, Diego de Landa in the 16th century explain us:

> God provided them with a flint range adjacent to the mountain range that ..., traverses the land, and from where they extracted stones from which they made the irons for the spears for war and the razors for sacrifices; they made the irons for the arrows and still make them, and thus the metal flint was useful to them. (Landa, 1556, p. 101).

At Sihó it has been reported (Fernández, 2010; Peniche y Fernández, 2004; Peniche, 2004) the work of siliceous materials such as flint or obsidian, from cortical removal of nodules to formatting artifacts, in the same archaeological contexts as the calcareous cobbles analysed. In addition, in many Maya communities natural resource extraction is still practised during agricultural practices documented at present in the same sampling area (Figure 4A, 3C).

In most Mayan archaeological sites, between the Preclassic and Postclassic, considering the archaeometric data, model and examples analysed, we find lithic resource exploitation spatial ratios lower than ten km, and in some exceptions, not exceeding thirty or forty km. These distances, are comparable to the suggested between Sihó and the nearest secondary geological sources on Ticul fault, for obtaining appropriate cobbles in a journey of work or even less (Figure 7). In Sihó's case, the involved work processes on Ticul secondary geological deposits exploitation, would be by hand or with the occasional use of tools such as digging sticks used in the maya agricultural practices, similar to those described by Diego de Landa: "they cultivate in many places

(...), and with a pointed stick they make a hole in the ground and put five or six grains in it, which they cover with the same stick" (Landa, 1556: 46). Once the cobbles were obtained from the geological deposits, they would have been transported to the settlement, distributed and used in different abrasive and/or percussion works.

To sum, we are dealing with an ancient social organisation of secondary geological resources explotation, centred on local limestone materials procurement, particularly cobbles with specific functional morphometric properties. These materials would be found at Ticul range in a working day time span, and would be used as abrasive and/or percussion tools with very little transformation. In addition, at present, in many Maya communities natural resource extraction is still practised regularly alongside agricultural practices, whose activities are actually reported in the same sampling area. These would be non-specialised economic activities, without major labour means investment in concept of relative surplus value,[4] practiced by a society that during Late and Terminal Classic mobilised a portion of its production forces, complementarily to other activities such as flint mining, and possibly including agricultural activities, to obtain certain calcareous lithic resources.

Conclusions

The aim of this study is to demonstrate the usefulness of archaeometric techniques to physicochemical identification of lithic material. Statistical elemental quantitative data processing between silicon (Si), calcium (Ca) and iron (Fe), obtained by X-ray fluorescence, provide us the possibility to discern calcareous materials from different geological formations and the potential links with archaeological samples. Furthermore, the comparison between the samples of archaeological cobbles and geological references ones, using sphericity indices calculations, offered a better identification of exploited lithic resources from secondary geological deposits. Thus, combining both data analyses we interpret a major archaeologic manuports petrographic concordance with transitional calcareous materials between the Upper Cretaceous and Early Palaeogene Icaiché formation, but mainly eroded and deposited at Ticul fault foot during the Pleistocene.

The applied theoretical and methodological model focuses on the different levels of resources social accessibility in a geographical territory and is developed as a relationship between its availability and social selection (Risch, 1995, 1998; Risch and Martínez, 2008), latter factor determined by the functioning of the production relations in a given social formation. In this

---

[4] Relative surplus value involves investment of production means and lies in opposite relation, although complementary, to the used work force increase (Marx, 1975; Risch, 1995). The italics are ours.

way, it would be a probability scale, rather than certainty about the lithic raw material extraction sites (Risch, 1995, 1998; Risch and Martínez, 2008).

Each sedimentary formation contains physicochemical features (chemical elements, minerals, fossils, etc.) which may help to recognise it among the others, depending on the geological strata diagenesis. However, due to the vast size of each formation, even with common diagenetic conditions, such features may be over-represented in wide areas of the same geological formations, becoming difficult to identify the sources of geological resources. We believe that single archaeological and reference material chemical identification is insufficient to identify a specific area as a geological source, especially in the primary deposits. Consequently, we consider it necessary to obtain independent archaeometric contrasting elements which enable us to quantify material relationship variability, whether chemical or physical, in order to specify the geological sources with more precision.

Also, we cannot discard the viability of qualitative contrast, as the identification of fossil contents, useful to discern geological ages which can characterise the studied geological formations. Similarly, the use of ethnographic or archaeological sources, such as quarry documentation, will be useful to propose stronger hypotheses about geological resource catchment areas in primary deposits. Conversely, the identification of secondary geological sources, whose materials have been formed by a natural agent in particular (colluvium, fluvial, maritime or glacial), may be more feasible if the lithic artefacts retain natural traits on their faces, as in our archaeological cases, independent and measurable from natural erosion. In conclusion, the lithic archaeological artefacts' independent variables provide analysis elements of geological materials, circumscribed in a physical (geological) space that can be socio-economically commensurable and categorised, according to the resource catchment model used.

Despite the methodological and archaeometric data limitations available, there is still much to do in terms of systematic qualitative and quantitative survey geological material deposit characterisation in the Yucatán Peninsula. In the future, the availability of a wider comparative reference sample for our archaeological materials, will provide data to better support the development of hypotheses about the economic management of geological resources by the ancient Maya.

Acknowledgements

To Dra. Lilia Fernández Souza from the Yucatan Autonomous University (UADY) and Dr. Javier Reyes Trujeque from the Corrosion Research Centre (CICORR), affiliated to the Campeche Autonomous University (UAC), for the support and resources provided for my doctoral thesis, origin and basis for this article. To

Dr. Adam Temple Sellen for his inestimable support and assessment in my current postdoctoral project at Peninsular Centre for Humanities and Social Sciences of the National Autonomous University of Mexico (CEPHCIS-UNAM).

References

Águila Flores, P. Del (1993). *Análisis de las piedras de moler desde una perspectiva arqueológica y Etnográfica [*Tesis de licenciatura, Universidad de San Carlos], Guatemala. http://biblioteca.usac.edu.gt/tesis/14/14_0150.pdf

Álvarez Jr., M. (1954). Exploración Geológica Preliminar del Río Hondo, Quintana Roo, *Boletín de la Asociación Mexicana de Geologos Petroleros*, 6, 207-213.

Aoyama, K. (1993). Sistemas de producción, distribución e intercambio comercial de la Lítica menor de obsidiana en el sureste de la zona maya. *VI Simposio de Investigaciones Arqueológicas en Guatemala, 1992* (pp. 431-436), Editado por J.P. Laporte, H. Escobedo y S. Villagrán de Brady, Museo Nacional de Arqueología y Etnología, Guatemala.
http://www.asociaciontikal.com/simposio-06-ano-1992/36-92-kazuo-aoyama-doc/

Braswell, G. E., y M. D. Glascock (1998). Artefactos de obsidiana del sureste de Petén" *Reporte 12, Atlas Arqueológico de Guatemala*, 499-525.

Bustillo, M. A., J. L. Pérez-Jiménez, M. Bustillo (2012). Caracterización geoquímica de rocas sedimentarías formadas por silicificación como fuentes de suministro de utensilios líticos (Mioceno, cuenca de Madrid). *Revista Mexicana de Ciencias Geológicas*, 29 (11), 233-247.
http://www.scielo.org.mx/pdf/rmcg/v29n1/v29n1a16.pdf

Cailleux, A. (1951). Morphoskopishe Analyse der Geschiebe und Sandkorner und ihre Bedeutung fur die Palaoklinatologie. *Geol. Rundch.,* 40, 5-13.
https://doi.org/10.1007/BF01803203.

Callejas Martínez, S. S. (2008). *Los artefactos líticos del Período Clásico en la cuenca del Motagua Medio* [Tesis de licenciatura, Universidad de San Carlos]. Guatemala. http://biblioteca.usac.edu.gt/tesis/14/14_0397.pdf

Clark, J. E. (1988). *The Lithic Artifacts of La Libertad, Chiapas, Mexico: An Economic Perspective, Papers of the New World Archaeological Foundation*, 52. Brigham Young University, Provo, Utah.

Cohen, K. M., S. C. Finney, P. L. Gibbard and J. X. Fan (2013). *The ICS International Chronostratigraphic Chart*, v. 2017, Episodes 36, pp. 199-204.
http://www.stratigraphy.org/ICSchart/ChronostratChart2017-02.pdf

Crabtree, D. E. (1968). Mesoamerican Polyhedral Cores and Prismatic Blades. *American Antiquity*, 33 (4), 446-478. https://doi.org/10.2307/278596

De Grooth, M. (1994). Die Versorgung mit Silex in der Bandkeramischen Siedlung Hienheim 'Am Weinberg' (Ldkr. Kelheim) und die Organisation de Abbus auf gebänderte Plattenhornsteine, im revier Arnhofen (Ldkr. Kelheim). *Germania*, 72 (2), 355-407. https://doi.org/10.11588/ger.1994.2

Delgado Raack, S. (2008). *Prácticas económicas y gestión social de recursos (macro)líticos en la prehistoria reciente (III–I milenios a.C.) del Mediterráneo occidental* [Tesis de doctorado, Departamento de Prehistoria] Universidad Autónoma de Barcelona.

https://www.tdx.cat/handle/10803/5528#page=1

Duch Gary, J. (1988). *La conformación territorial del Estado de Yucatán. Los componentes del medio físico*, Universidad Autónoma de Chapingo, Centro Regional de la Península de Yucatán. México.

Fernández Souza, L. (2010). *Grupos domésticos y espacios habitacionales en las Tierras Bajas Mayas durante el Período Clásico* [Tesis doctoral, Universidad de Hamburgo]. https://d-nb.info/1002565839/34

Flores, D. A. (1974). Los suelos de la República Mexicana. *El escenario geográfico. Recursos naturales*, SEP/INAH, México.

Gallegos Gomora, M. J. (1994). Explotación de piedra caliza en el Petén campechano. *Mayab*, 8-17. https://www.academia.edu/2049695/Explotaci%C3%B3n_de_piedra_caliza_en_el_Pet%C3%A9n_campechano

Garza Tarazona, S. y E. B. Kurjack (1980). *Atlas Arqueológico del Estado de Yucatán*, 2 vol. INAH, México.

García Gil, G., y E. Graniel Castro (2010). Geología. *Biodiversidad y desarrollo humano en Yucatán, Contexto físico*, 1, 4-26, editado por R. Durán y M. Méndez, Centro de Investigación Científica de Yucatán, Programa de Pequeñas Donaciones en México del Fondo para el Medio Ambiente Mundial, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, Secretaría de Desarrollo Urbano y Medio Ambiente. Mérida, Yucatán, México. https://www.cicy.mx/sitios/biodiversidad-y-desarrollo-humano-en-yucatan

González Cruz, A., y M. Cuevas García (1990). *Artefactos clandestinos. Los cantos rodados y los procesos de trabajo asociados a la construcción de edificios públicos en el centro de Chiapas* [Tesis de licenciatura, Escuela Nacional de Antropología e Historia].

Guzzy Arredondo, P. y A. González Cruz (1988). Una industria de cantos rodados en el sureste de Mesoamérica, *Arqueología*, 3, 29-46. https://www.revistas.inah.gob.mx/index.php/arqueologia/article/view/13488

Hammer, O., D. A. T. Harper and P. D. Ryan (2001). Paleontological Statistics software package for education and data analysis. *Palaeontologia Electronica*, 4 (1), 9. http://palaeo-electronica.org/2001_1/past/issue1_01.htm

Hayden, B. (1987). Traditional Metate Manufactuing in Guatemala Using Chipped Stone Tools, *Lithic studies among the contemporany Highland Maya* (pP. 8-111). Editado por B. Hayden, The University Arizona Press, Tucson.

Hirth, K. G. (2009). Household, Workshop, Guild, and Barrio: The Organitzation of Obsidian Craft Production in a Prehispanic Urban Center". Domestic Life in Prehispanic Capitals: A Study of Specialitzation, Hierarchy and Ethnicity, no. 46, pp. 43-65, edited by L.R. Manzanilla and C. Chapdelaine, Museum of Anthropology, University of Michigan, Ann Arbor.

Howard, J. L. (1993). The statistics of counting clasts in rudites: a review, with examples from the upper Palaeogene of southern California, USA, *Sedimentology*, 40, 157-174. https://doi.org/10.1111/j.1365-3091.1993.tb01759.x

Jiménez Álvarez, S. (2007). *Sihó: una unidad política del occidente de Yucatán* [Tesis de maestría, Facultad de Ciencias Antropológicas], Universidad Autónoma de Yucatán.

Jiménez Álvarez, S., R. Cobos, H. Chung y R. Belmar Casso

2006 El despertar de la complejidad sociocultural visto desde el estudio tecnológico de la cerámica: Explicando las transformaciones sociopolíticas en el occidente de Yucatán. En B. A. Laporte y H. Mejía, (Eds.), *XIX Simposio de Investigaciones Arqueológicas en Guatemala, 2005* (pp. 532-542), Museo Nacional de Arqueología y Etnología, Guatemala.
http://www.asociaciontikal.com/simposio-19-ano-2005/49-socorro-et-al-05-digital-doc/

Kidder, A. V. (1947). *Los Artefactos de Uaxactún Guatemala*, Institución Carnegie de Washington, Washington, D. C.
https://publicationsonline.carnegiescience.edu/publications_online/LosArtefactosDeUaxactunGuatemala.pdf

Landa, D. De (1556). *Relación de las cosas de Yucatán*.
http://www.wayeb.org/download/resources/landa.pdf

López Ramos, E. (1977). Estudio Geológico de la Península de Yucatán. *Enciclopedia Yucatanense*, 10. https://www.amgp.org/api/administration/publicaciones/5da7505d3fed8_1973_Ene_Mzo_02.pdf

Lütting, G. (1956). Eine neue, einfache gerollmorphometrische Methode, *Eiszeitlalter und Gegenwart*, 7, 13-20. https://egqsj.copernicus.org/articles/egqsj-volume7.pdf

Madrid González, M. V. (2013). *Análisis morfológico de los artefactos líticos de molienda del asentamiento prehispánico de Piedra Labrada, Veracruz* [Tesis de licenciatura, Universidad Veracruzana]. https://www.academia.edu/28627665

Marín Stillman, L. E., J. G. Pacheco Ávila y R. Méndez Ramos (2004). "Hidrogeología de la Península de Yucatán. *El agua en México vista desde la Academia*, 10, 159-177, editado por B. Jiménez y L. Marín, Academia Mexicana de Ciencias. México, D.F.
https://docplayer.es/35750380-Hidrogeologia-de-la-peninsula-de-yucatan.html

Marx, K. (1975). *El Capital. Crítica de la economía política, el proceso de producción de capital, Tomo I*. Madrid. Siglo Veintiuno Editores S.A.
http://ecopol.sociales.uba.ar/wp-content/uploads/sites/202/2013/09/Marx_El-capital_Tomo-1_Vol-1.pdf

Mijangos Pantaleón, B. A. (2014). *Las piedras y manos para moler del sitio Salinas de los Nueve Cerros. Implementos utilizados en el refinamiento de sal* [Tesis de maestría, Universidad de San Carlos] Guatemala.
http://biblioteca.usac.edu.gt/tesis/14/14_0516.pdf

Moholy-Nagy, H. (2003). Source Attribution and Utilitzation of Obsidian in the Maya Area. *Latin American Antiquity*, 14, 301-310. https://doi.org/10.2307/3557561

Morán Aragón, P. R. (2013). *Materiales de piedra para molienda del Proyecto Arqueológico Cotzumalguapa. Santa Lucía Cotzumalguapa, Escuintla* [Tesis de licenciatura, Universidad de San Carlos], Guatemala.
http://biblioteca.usac.edu.gt/tesis/14/14_0505.pdf

Pastrana, A. (1986). El proceso de trabajo de la obsidiana de las minas de Pico de Orizaba. *Boletín de Antropología Americana*, 13, 133–145.
http://www.jstor.org/stable/40977916

Pat Cruz, D. (2006). *Análisis de las Piedras de Molienda de Sihó, Yucatán* [Tesis de maestría, Facultad de Ciencias Antropológicas], Universidad Autónoma de Yucatán.

Peniche, N. M. (2004). *Aspectos de la organización económica de grupos domésticos de élite: Las industrias de talla de sílex de Sihó, Yucatán* [Tesis de maestría, Facultad de Ciencias Antropológicas], Universidad Autónoma de Yucatán. https://www.academia.edu/9694362

Peniche May, N. y L. Fernández Souza (2004). En la búsqueda de actores sociales: Los artefactos líticos de Siho, Yucatán, *XVII Simposio de Investigaciones Arqueológicas en Guatemala, 2003*, pp. 903-912, editado por J. P. Laporte, B. Arroyo, H. Escobedo y H. Mejía, Museo Nacional de Arqueología y Etnología, Guatemala.

Pétrequin, P. y C. Jeunesse (1995). *La hache de Pierre. Carrièrres vosgiennes et échanges de lames polies pendant le Néolithique (5400-2100 av. J.C)*, Errance, Paris. https://www.academia.edu/26435332

Proskouriakoff, T.

1962 The Artifacts of Mayapan. En H. E. D. Pollock, R. L. Roys, A. Ledyard Smith and T. Proskouriakoff (Eds.), *Mayapan, Yucatan, Mexico, no. 619* (pp. 321-442), Carnegie Institution of Washington, Washington. https://openlibrary.org/books/OL5876784M/Mayapan_Yucatan_Mexico

Risch, R. (1995). *Recursos naturales y sistemas de producción en el sudeste de la Península Ibérica entre 3000 Y 1000 ANE*, Departamento de Prehistoria, Universidad Autónoma de Barcelona.

Ruiz Aguilar, M. E. (1986). Análisis preliminar de la lítica de Mundo Perdido, Tikal. *Mesoamérica*, 11, 113-133. file:///C:/Users/llore/Downloads/Dialnet-AnalisisPreliminarDeLaLiticaDeMundoPerdido-4008998%20(1).pdf

Ruiz Aguilar, M. E. (2007). El material de molienda de los Altos Orientales de Chiapas, México. En J. P. Laporte, B. Arroyo y H. Mejía (Eds.), *XX Simposio de Investigaciones Arqueológicas en Guatemala, 2006* (pp. 1284-1301). Museo Nacional de Arqueología y Etnología, Guatemala. http://www.asociaciontikal.com/wp-content/uploads/2017/01/79.06_-_Malena.pdf

Ruiz Aguilar, M. E. (2019). Alisadores de estuco en el área Maya. *Estudios de Cultura Maya*, 53, 43-63. https://revistas-filologicas.unam.mx/estudios-cultura-maya/index.php/ecm/article/view/987

Servicio Geológico Mexicano (2007). *Yucatán, Campeche y Quintana Roo, Carta Geológico-Minera, 1:500,000.*

Shafer, H. J., and T. R. Hester (1991). Lithic Craft Specialization and Product Distribution at the Maya Site of Colha, Belize. *Craft Production and Specialization, World Archaeology*, 23 (1), 79-97. https://doi.org/10.1080/00438243.1991.9980160

Sheets, P. D. y R. Gallardo (2013). Joya de Cerén: Patrimonio Cultural de la Humanidad, 1993-2013. *Colección Antropología y Arqueología*, 1. https://www.colorado.edu/anthropology/sites/default/files/attached-files/joya_sheets_23_oct_2013.pdf

Taladoire, E. (2016). Las bases económicas de una entidad política maya. El caso de Toniná. *Estudios de cultura maya*, 48, 11-37. https://doi.org/10.19130/iifl.ecm.2016.48.753

Taube, K. A., Hruby, Z. and L. Romero (2011). Ancient Jade Workshops: Archaeological Reconnaissance in the Upper Río El Tambor, Guatemala. *The Technology of Maya Civilitzation: Political Economy and Beyond in lithic Studies*. Equinox Press. https://doi.org/10.4324/9781315728858

Titmus, G. L. y J. C. Woods (2002). Un estudio arqueológico y experimental de las canteras antiguas de Nakbe, Petén, Guatemala. En P. Laporte, H. Escobedo y B. Arroyo (Eds.), *XV Simposio de Investigaciones Arqueológicas en Guatemala, 2001*, (pp. 188-201). Museo Nacional de Arqueología y Etnología, Guatemala. http://www.asociaciontikal.com/simposio-15-ano-2001/17-01-titmus-y-woods-doc/

Tucker, M. E. (1991). *Sedimentary petrology: an introduction to the origin of sedimentary rocks*. London. Blackwell Science.