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The Detachment Physical Weathering Form Group Affecting Stone Building Materials at The Archaeological Site of Sabratha, Northwest Libya

Ismail F. Shushan[1, *], Sadik B. Akhmyra[1], and Haitham A. Minas[2]

[1]Department of Geology, Faculty of Sciences, Elmergib University, Al-Khoms city, Libya.

[2]Department of Geology, Faculty of Sciences, Former Elmergib University Staff member, Al-Khoms city, Libya.

[*]**Corresponding author:** elforjismail@yahoo.com

مجموعة التجوية الفيزيائية الانفصالية المؤثرة على مواد صخور البناء بمدينة صبراتة الأثرية، شمال غرب ليبيا

إسماعيل الفرجاني الشوشان[1، *]، الصادق بشير أخميرة[1]، و هيثم أمير ميناس[2]

[1]قسم علوم الأرض، كلية العلوم، جامعة المرقب، الخمس، ليبيا.

[2]عضو هيئة تدريس سابق بقسم علوم الأرض، كلية العلوم، جامعة المرقب، الخمس، ليبيا.

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Abstract

The archaeological Sabratha City is a UNESCO World Heritage site located on the Mediterranean Sea coast west of the Capital City of Tripoli north of Libya. Like many other archaeological cities in the world, Sabratha monuments have been built using naturally existing stones which according to the rules of nature are subjected to continuous weathering processes and become damaged to varied degrees. The range of extension as well as the type of stone damage is dependent on the reacting stone materials with the natural weathering processes. From an important point of view, the preservation of stone monuments now has attained the care of the government institutions who are in concern. The present paper discusses the main physical weathering forms belonging to the weathering form group-3 "the detachment group" which has been established by (Fitzner, and Heinrichs, 2002, 2004). The methodology of this research will be based on applying certain forms invented by Fitzner and Heinrichs that serve to estimate every damage of weathering forms affecting the monuments of Sabratha City. A number of nine main weathering forms of the detachment group including about fifteen individual weathering forms were found to affect the whole monuments of the city with damage intensity degrees varied between non-visible damage and moderate damage (0 degrees and 3 degrees). To make it easy for observations, fifteen contour maps were drowning for each individual weathering form showing the damage intensity degree and distribution. To summarize the overall picture of the weathering form damages, linear and progressive damage indices were found and mapped. Diurnal and seasonal temperature variations; relative humidity fluctuations; salt crystallization; moisture and or water content are factors expected to produce such weathering damages. As a recommendation, the authorities in response are invited to take this matter seriously and should act to protect the built heritage of Sabratha City.

Keywords: *Detachment physical weathering group, Weathering of Sabratah stone building material, Physical weathering effects stone monuments.*

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الملخص

تُعد مدينة صبراتة الأثرية ضمن الإرث العالمي لليونيسكو (UNESCO World Heritage) والواقعة على ساحل البحر المتوسط، غرب العاصمة طرابلس بالشمال الليبي. وكمثيلتها بالمدن الأثرية الأخرى في العالم، فقد تم بناءها باستخدام الأحجار الصخرية المتكونة طبيعيا فهي بالتالي تتعرض باستمرار لعوامل التعرية التي تتحكم فيها قوانين الطبيعة محدثة بها أضرارا على درجات مختلفة من الشدة. يعد التفاعل ما بين مواد صخور الأبنية الأثرية وعوامل التعرية الطبيعية المسئول عن نوع الأضرار الناتجة وكذلك درجة شدة انتشارها. وكنتيجة للوعي المتزايد والاحترام تجاه المباني الأثرية فان حمايتها من كل الأضرار أصبح شأن كبير عند كل من ساسة الدول والشعوب. يناقش البحث الحالي أشكال التعرية الفيزيائية الرئيسية والتابعة للمجموعة الثالثة المعروفة بالانفصال "Detachment Group" أحد مجاميع التعرية التي ابتكرها (Fitzner and Heinrichs, 2002, 2004). اعتمدت طريقة البحث على استخدام نماذج معدة بواسطة Fitzner و Heinrichs والتي من شأنها إظهار وتقدير أضرار التجوية الانفصالية الفاعلة على مواد صخور بناء مدينة صبراتة الأثرية. تم رصد تسع أشكال رئيسية للتجوية الانفصالية متضمنة ما يقارب خمسة عشر شكلا لإشكال التجوية المؤثرة والتي تؤثر على صخور مواد البناء للمدينة محدثة أضرارا بمباني المدينة تراوحت درجة شدتها ما بين الضرر غير واضح والضرر المعتدل. ولتسهيل عملية تتبع هذه الأضرار في المدينة، تم إنشاء خمسة عشر خارطة كنتورية لكل ضرر من أشكال التجوية المؤثرة موضحا عليها درجة شدة الضرر ومدى انتشارها في كل نواحي المدينة. ولإظهار إجمالي تأثير هذه الأضرار المرصودة على أبنية المدينة، تم تقدير دليلي التدهور الخطي والتقدمي لإشكال التجوية وتم إنشاء خريطة كنتورية لكل منهما. يتوقع أن التغيرات اليومية والفصلية لدرجة الحرارة وكذلك التقلبات التي تطرأ على الرطوبة النسبية للجو بالإضافة الى عمليات التبلور الملحي فوق أسطح الأبنية ونسبة البلل أو محتوى الماء المحصور في مواد صخور الأبنية، كلها عوامل بإمكانها إحداث أضرارا لهذا النوع من التجوية. تم رفع توصيات تضمنت الدعوة إلى استكمال دراسة بقية أنواع التجوية المؤثرة على أبنية مدينة صبراتة الأثرية وكذلك دعوة المسؤولين في الدولة لحماية أبنية المدينة من الانهيار نتيجة لأضرار التجوية.

الكلمات الدالة: مجموعة التجوية الفيزيائية الانفصالية، تجوية مواد الصخور بمدينة صبراتة الأثرية، التجوية الفيزيائية المؤثرة على أحجار البناء الأثرية.

1. Introduction

Usage of natural stones for buildings and monuments may characterized the history of mankind through the live, which with the passage of time, they become affected by weathering processes. (Fiitzner and Heinrichs, 2002, 2004). Weathering can be physical, chemical or biological. Physical or mechanical weathering is the process by which a natural rock become fragmented into smaller pieces without changing in its chemical composition. While chemical weathering is the process that acting on the rock and causing chemical reactions that lead to generation of new minerals especially when become in contact with bodies of water at near surface environment. Biological weathering is the interaction between the activity of any biological sources such as plants, animals and others with the surface of different types of rocks and may damage them through secretion of acidic compounds (Pamela, 2013; Zambell *et al*., 2012; Uroz *et al*., 2009; Goudie and Viles, 2008; and Calvaruso *et al*., 2006). Monuments that are not maintained sufficiently or are not restored appropriately will be surely subjected to stone damage. Recently, a new techniques and research technologies were introduced to study the damage characteristics and monument restoration activities (Fiitzner and Heinrichs, 2002, 2004). In this domain, Fitzner and Heinrichs explained the principles of evaluation concerning weathering of monument stone materials. In this context, they defined the classification scheme of weathering forms (level 1: group of weathering forms, level 2: main weathering forms, level 3: individual weathering

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forms, level 4: intensities or parameters). Beside to these, they have also referred to the damage categories and the damage indices of the Weathering forms. In general, they defined (4) groups of weathering forms (group 1: loss of stone material divided to (3) main weathering forms and (18) individual weathering forms and (3) classes of intensities or parameters, while group 2: discoloration/deposits divided to (9) main weathering forms and (25) individual weathering forms and about (14) classes of intensities or parameters, while group (3) the detachment is divided to (11) main weathering forms and about (11) individual weathering forms and (12) classes of intensities or parameters, the last group (4) is the fissures/deformations which is divided to (2) main weathering forms and about (4) individual weathering forms and about (3) classes of intensities or parameters). The present research which concerning with Sabratah archaeological site will discusses only the weathering form group (3) that affects the stone building materials. The weathering form group (1): "the loss of stone material" that affects the stone building materials of Sabratah monuments has been discussed earlier (Shushan *et al.*, 2019).

2. Location and Definition of the Study Area

The archaeological Sabratha City is located on the Mediterranean Sea coast about 70 km (43 miles) west of the Capital City of Tripoli north of Libya, within the coordinates: 32°47′32″N and 12°29′3″E as shown in Figure (1). It is bordered by the sea from north, Zawiyah City to the east, Jafara to the southeast, Yafran to the south and Zuwarah City to the west. This archaeological site become as a UNESCO World Heritage Site in 1982 (Agence France-Presse, 2017; Francois Decret, 2011; and Sha'biyat of Great Jamahiriya 2009).

Sabratha has been known as an old port city along North Africa coast which is in now days known as Libya State. The Berber Zwagha tribe were have been known to occupy Sabratha Site and gave it their name in the 8th century BCE (as noted by the historian Al-Bakari, 11th-century CE). Sabratha became a Carthaginian Colony under the name of Tsabatan and have been a part of tri-city trade network for Greeks recognized as Emporia. The Site of Sabratha was taken by Numidians in (c. 202-148 BCE) after the death of Carthage in the 2nd Punic War in (c. 218-202 BCE) and it has been governed then by Masinissa' grandson Jugurtha in (r. 118-105 BCE) . It was taken then by Rome after Jugurtha's death in (105 BCE) and during the reign of Julius Caesar (48-44 BCE) it became a part of Africa Nova Province (Mark, 2019).

3. Statement of The Research Problem and Objectives

Before the year 1911 CE, the Monuments of Sabratha Site were located under the sand as being buried due to sea and wind storm action. The city was recovered by excavation activities brought by the Italian government in 1911 CE (Mark, 2019).

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Figure 1. Location of study area (the red arrow)

Sabratha Monuments were undergone dangerous periods of erosion were buildings become crumbled due to storm and unsettled sea conditions (Agence France-Presse, 2017; Francois Decret, 2011; and Sha'biyat of Great Jamahiriya 2009). The main goal of this research is to evaluate the physical weathering damages on the stone building materials of Sabratha monuments caused by weathering group (3) which is the "Detachment Group" This will include: classification of the damages of each weathering group as discussed by (Fitzner and Heinrichs, 2002 and 2004) (ex. Main Weathering form, individual weathering form, weathering intensity), establishing the location and distribution of each class of weathering damages within the ancient Sabratha City, mapping of each type of weathering damage intensities that affect the stone building materials and mapping of the "linear and progressive Deterioration indices- LDI and PDI" of group (3) of weathering forms.

Methodology of this research will be based on applying certain forms invented by (Fitzner *et al.*, 2002 and 2004) that serve to estimate every damage of weathering form. This include estimation of the damage intensity percentages (%), estimation of the damage intensity categories and measurement of flakes thicknesses (mm) that detaching from the stone building materials at Sabratha monuments.

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4. Stratigraphy of The Study Area

The area of study is surrounded from the south and south-east by a series of rock units belonging to Jabal Nafusa (Nafusa Mountain) which have been used as row materials from which stone buildings were prepared to establish the monuments of Ancient Sabratha City. The distance between Sabratha City and the Jabal Nafusa Series is about 86.19 km. The area of study is covered by rock units limited between the Late Triassic and Quaternary. The study of El Hinnawy and Cheshitev (1975) made on Jabal Nafusa and the surrounding areas is used to classify and define the different rock units outcrop in the area which is summarized in the stratigraphic column shown in Figure (2).

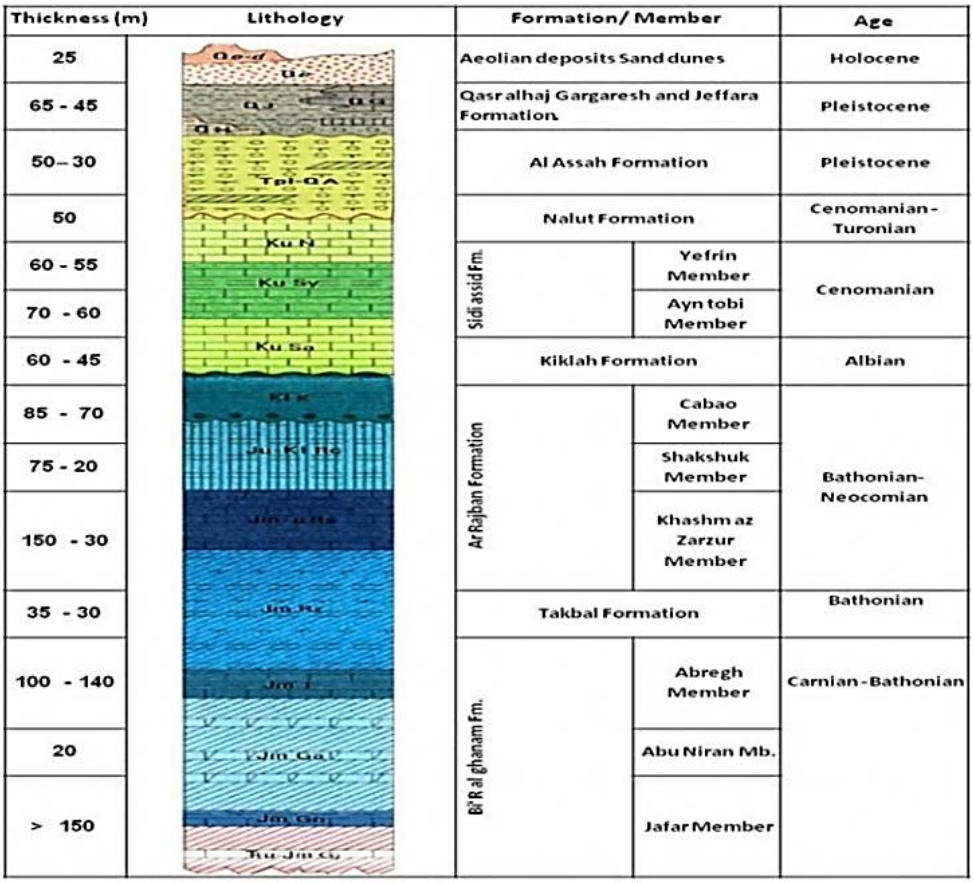

Figure 2. The stratigraphic succession of Jabal Nafusa and the surrounding areas (El Hinnawy and Cheshitev, 1975).

5. Results and Discussion

The investigation done in the area of study concerning the evaluation of the damages caused by weathering form group (3) has followed the map shown in Figure (3).

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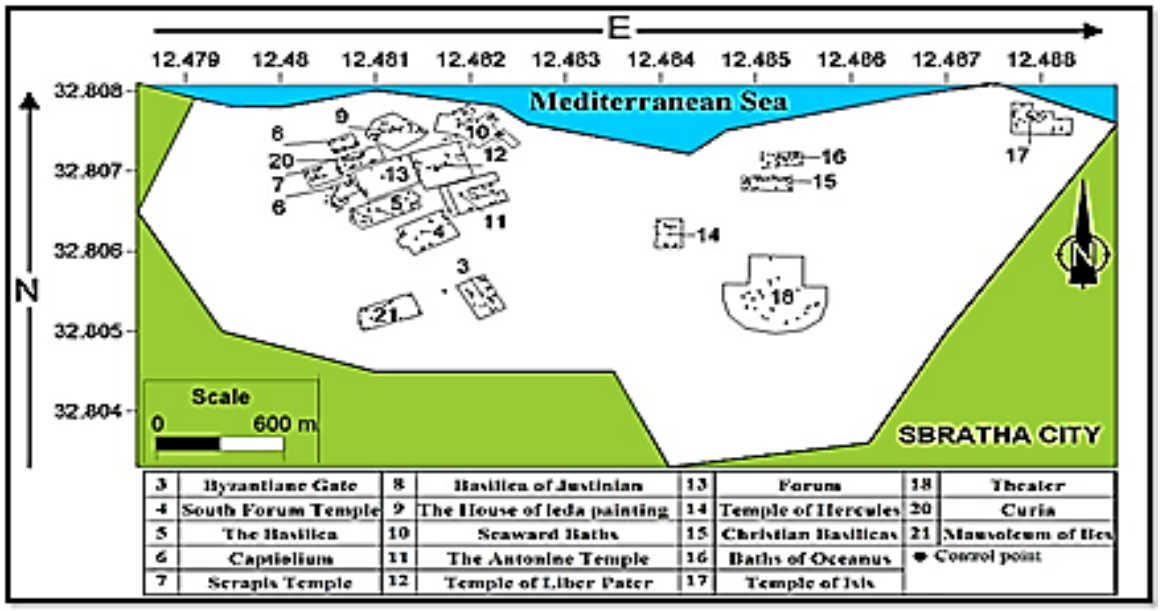

Figure 3. Locations of the studied monuments at Ancient Sabratha City

The results of weathering form group (3) "Detachment" affecting the studied monuments at Ancient Sabratha City are summarized in (Tables 1-5).

The results of the calculated damage indices (Linear and Progressive damage indices) for weathering form group-3 that effect the stone monuments at Sabratha City is represented in Table (2). In order to conclude the conclusive quantification and rating of weathering damage effect on stone monuments, the damage indices were applied. According to calculation modes effectuated by (Fitzner and Heinrichs, 2000), the damage indices may range between (0 and 5). The linear damage index (Map 16) refers to the average damage category, whereas the progressive damage index (Map 17) refers to the proportion of higher damage categories (Fitzner *et al*., 2000; and Heinrichs, and Fitzner, 1999).

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Table 1. Presentation of results belonging to weathering form group-3 that affect stone building materials at Sabratha monuments*.

Main weathering forms	Individual weathering forms	Damage intensity Category	Name of affected monuments (refer to Figure (3))	Map and photo reference
		0 1 2 3 4 5		
Flaking (F)	Single flakes (sf)	0 1	Nr.3 to 21	Map-1
	Multiple flakes (mf)	0 1	Nr.3 to 21	Map-2, Photo-1
Flaking to contour scaling (F-S)	Single flakes to single scales (sf-ss)	0 1	Nr.3 to 21	Map-3
	Multiple flakes to multiple scales (mf-ms)	0 1	Nr.3 to 21	Map-4
Flaking to crumbly disintegration (F-P)	Single flakes to crumbling (sf-c)	0	Nr.3 to 21	Map-5
Contour scaling (CS)	Single scale (ss)	0	Nr.3 to 21 (except 15,16,17)	Map-6, Photo-2
	Multiple scales (ms)	0 1	Nr.3 to 21	Map-7, Photo-3
	Scale due to tooling of the stone surface (st)	1 2	Nr.3 to 21	Map-8
Granular disintegration (G)	Granular disintegration into grus (Gg)	1 2	Nr.3 to 21	Map-9
	Granular disintegration into powder(Gp)	1 2 3	Nr.3 to 21	Map-10, Photo-4
Granular disintegration to flaking (GF)	Granular disintegration into sand to single flakes (Gsf)	0 1	Nr.3 to 21	Map-11
Crumbly disintegration (P)	Splintering (sp)	1 2	Nr.3 to 21	Map-12
	Crumbling to splintering (c-sp)	1 2	Nr.3 to 21	Map-13
Crumbly disintegration to contour scaling (P-S)	Crumbling to single scale (c-ss)	0	Nr.3 to 21	Map-14
Detachment of stone layers dependent on stone structure (X)	Exfoliation (ex)	0	Nr.3 to 21	Map-15

*See Annex A, "Explanations of terminology and abbreviations"

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Table 2. Estimation of damage intensity percentages (%) of detachment group of weathering that affecting the stone building materials at Sabratha monuments according to damage category groups established by (Fitzner *et al.*, 2002).

Sabratha Archaeological Sites	Group-3- Detachment Damage Category (%)				
	Very Slight	Slight	Moderate	Severe	Very Severe
Byzantiane Gate	27	20	41	11	0
South Forum Templle	15	44	0	42	0
The Basilica	49	13	34	4	0
Captiolium	59	10	19	11	0
Scrapis Temple	48	9	33	11	0
Basilical of Justiian	19	34	31	15	0
The House of Leda panting	6	37	37	20	0
Seaward Baths	29	25	33	13	0
The Antonine Temple	37	28	13	22	0
Temple of Liber Pater	45	19	23	13	0
Forum	33	0	33	33	0
Temple of Hercules	60	26	6	8	0
Christian Basilica	32	40	0	28	0
Baths of Oceanus	25	3	40	32	0
Temple of Isis	31	36	26	6	0
Theater	45	15	19	20	0
Curia	68	6	6	20	0
Mausoleum of Bes	23	36	17	24	0

Table 3. Estimation of damage intensity of detachment weathering group that affecting the stone building materials at Sabratha monuments according to damage category groups established by (Fitzner *et al.*, 2002).

Sabratha Archaeological Sites	Weathering Detachment Group-3									
	Detachment thickness "mm									
	sf	mf	st	ss	ms	ex	Sf-c	c-ss	Sf-ss	mf-ms
Byzantiane Gate	2	1	3	1	1	1	4	3	4	1
South Forum Templle	2	4	4	2	4	2	1	1	1	4
The Basilica	2	3	3	3	4	3	1	1	1	4
Captiolium	1	1	4	1	4	1	3	1	1	3
Scrapis Temple	2	4	3	1	1	3	1	1	1	1
Basilical of Justiian	2	4	3	3	2	4	4	3	3	1
The House of Leda panting	2	4	4	3	3	3	3	1	3	4
Seaward Baths	1	1	3	1	1	1	1	4	2	4
The Antonine Temple	3	4	4	2	3	4	1	1	2	4
Temple of Liber Pater	1	1	4	1	1	1	1	1	1	1
Forum	3	4	3	3	4	1	1	1	1	1
Temple of Hercules	2	4	1	1	1	3	1	1	1	1
Christian Basilica	2	4	4	1	1	1	1	4	2	1
Baths of Oceanus	2	4	4	1	4	3	4	1	1	3
Temple of Isis	1	1	3	1	1	4	1	2	2	1
Theater	3	1	4	1	1	1	1	1	1	1
Curia	2	4	4	1	3	1	1	1	1	1
Mausoleum of Bes	1	1	3	4	1	1	4	4	4	1

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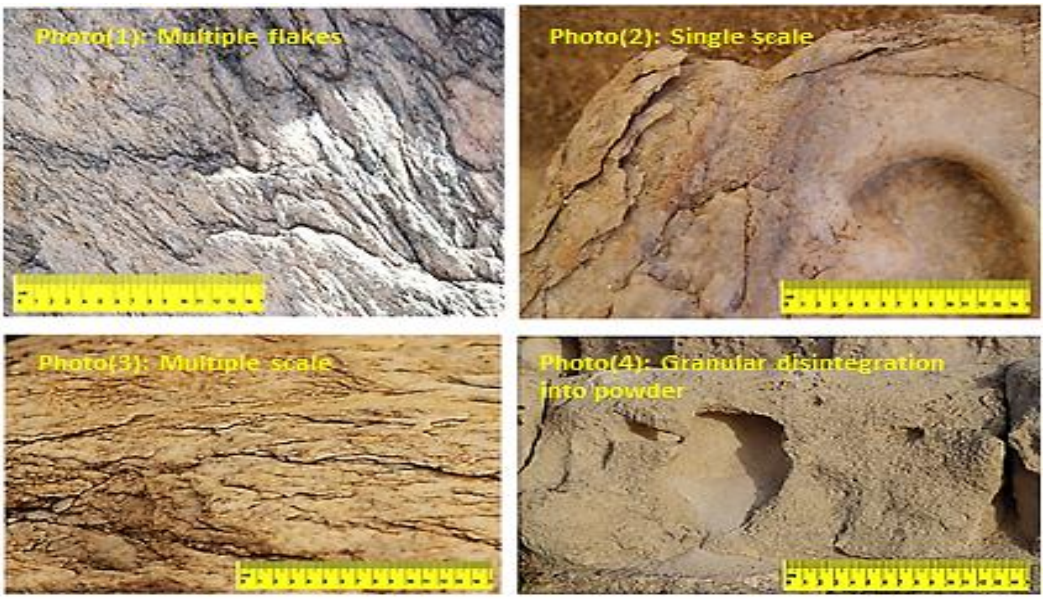
Table 4. Measurement of flakes thicknesses (mm) detached from the stone building material at Sabratha monuments according to category groups established by (Fitzner *et al*., 2002).

Sabratha Archaeological Sites	Weathering Detachment Group Detachment thickness "mm"									
	Thickness of detached flakes "mm"									
	sf	**mf**	**st**	**ss**	**ms**	**Ex**	**Sf-c**	**c-ss**	**Sf-ss**	**mf-ms**
Byzantiane Gate	2.6	0	6	0	0	0	10.8	9.6	32.6	0
South Forum Templle	2.5	15.2	15.6	2.8	14.6	4.4	0	0	0	20.6
The Basilica	4.3	9.2	6.7	9.4	10.6	7	0	0	0	57.2
Captiolium	0	0	10.2	0	20.2	0	6	0	0	6
Scrapis Temple	3.5	20	9.6	0	0	6	0	0	0	0
Basilical of Justiian	4.1	23.8	7	8.6	27.4	3.8	23.8	7.6	9.4	0
The House of Leda panting	4.8	17.8	10.4	7.8	8	5.4	7	0	8.4	20.6
Seaward Baths	0	0	9.4	0	0	0	0	54	3.4	10.4
The Antonine Temple	5.1	24.4	18.8	3.9	6	-	0	0	4.8	30.6
Temple of Liber Pater	0	0	34.6	0	0	0	0	0	0	0
Forum	7.6	26.4	5.6	5.8	78.2	0	0	0	0	0
Temple of Hercules	3.5	15.4	0	0	0	5.6	0	0	0	0
Christian Basilica	4.4	17.8	11.4	0	0	0	0	11	4.4	0
Baths of Oceanus	4.8	17.6	15	0	10.6	6	78	0	0	6
Temple of Isis	0	0	8.4	0	0	10.5	0	3.4	3.9	0
Theater	5.6	0	11	0	0	0	0	0	0	0
Curia	2.6	12.8	11.4	0	8.8	0	0	0	0	0
Mausoleum of Bes	0	0	7	38.2	0	0	53.4	52	17.6	0

Intensity	Thickness "mm"				
	< 2	2-5	5-10	10-20	> 20
Damage category	1	2	3	4	5



Photographs refer to Table (1). Close-up views representing 3 types of individual weathering forms belonging to "Flaking; photo1, Contour scaling; photos: 2 and 3, Granular disintegration; photo: 4" which is part of the main weathering form group-3 "Detachment".

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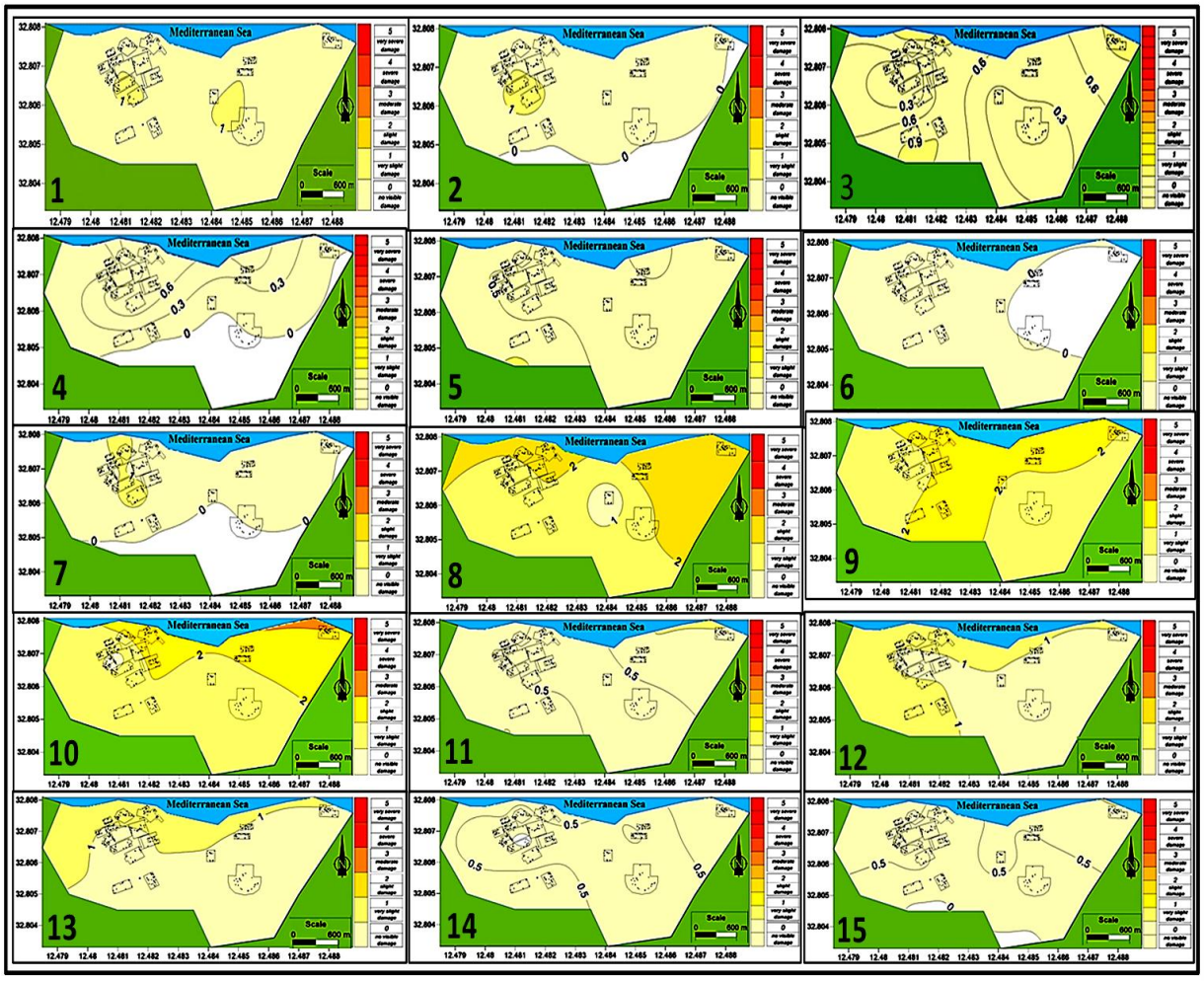

Maps refer to Table (1). Damage intensities and distribution of individual weathering forms group-3 that affect the Ancient Sabratha Monuments (Map-1: Single flakes; Map-2: Multiple flakes; Map-3: Single flakes to single scales; Map-4: Multiple flakes to multiple scales; Map-5: Single flakes to crumbling; Map-6: Single scale; Map-7: Multiple scale; Map-8: Scale due to tooling of the stone surface; Map-9: Granular disintegration into grus; Map-10: Granular disintegration into powder; Map-11: Granular disintegration into sand to single flakes; Map-12: Splintering; Map-13: Crumbling to splintering; Map-14: Crumbling to single scale; Map-15: Exfoliation).

Table 5. The linear and progressive deterioration results

Weathering Form Group	Weathering Damage Index	Damage Category						Dispersion (refer to Figure (3) and maps (16 and 17)	Notes
		0	1	2	3	4	5		
Group-3 Detachment	Linear Deterioration Index (LDI)							widespread	Map-16
	Progressive Deterioration Index (PDI)							widespread	Map-17

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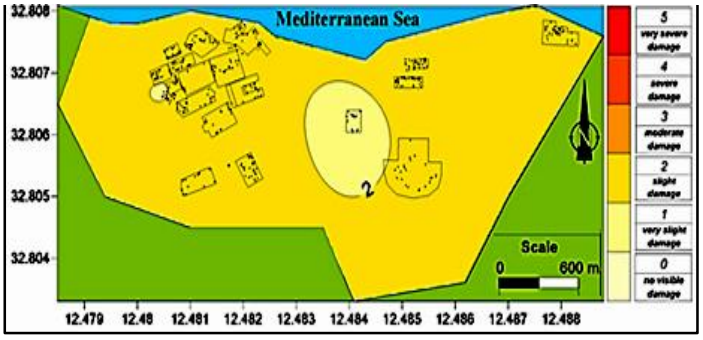
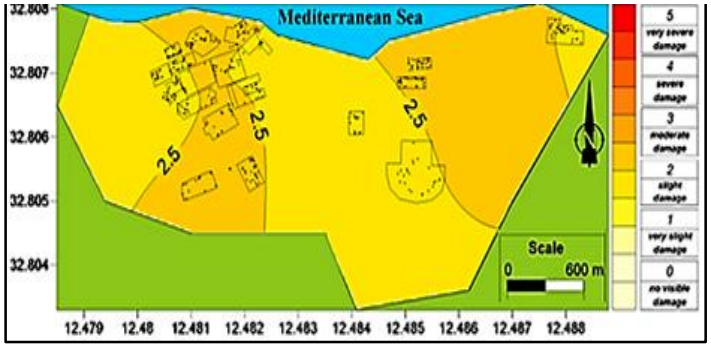


Map-16 refers to Table (1). Distribution and intensity of the linear deterioration index belonging to weathering form group-3 that effect stone monuments at Sabratha City.



Map-17 refers to Table (1). Distribution and intensity of the progressive deterioration index belonging to weathering form group-3 that affect stone monuments at Sabratha City.

Many factors of mechanical weathering were considered to be effective to create such damages like that established on stone monuments of Sabratha City, which may include expansion and contraction of the building stone materials caused by temperature variations between day and night and from summer to winter seasons, freezing and thawing cycles can create damages to the monuments, salt crystallization can also produce damages on stone monuments, fluctuations in relative humidity can also change the overall composition of stone monuments and may damages them, the moisture content (water adsorbed by rock materials) especially clays may swell and cause damage to surrounding rock materials of stone monuments (Gore Pamela, 2013; Zambell *et al*., 2012; Uroz *et al.*, 2009; Goudie, and Viles, 2008; Calvaruso *et al.*, 2006; National geographic Society, 1996-2019). According to the results shown above, the degree of intensity range of each individual form of weathering affecting the stone building materials of Sabratha monuments are generally speaking closely similar with few exceptions in certain sites which may owing in part to the similarity in the lithology and type of stone buildings and in the other part to the type (types) of mechanical weathering agents acting in the region. As a matter of fact durable and resistant stone building materials are off course more resistible to weathering agents. Therefore, the degree of intensity range of the individual weathering forms discussed here is directly proportional to degree of resistivity and durability of the stone building materials of the monuments. We also mention that the overall original texture of stone building materials of the monuments can

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play an important role in accelerating the weathering process. The close similarity in the degree of intensity range of the individual weathering forms has been emphasized also through the results of the linear and progressive damage indices showed in Table (2) and (Maps 16 and 17).

5. Conclusion

The weathering form group-3 "the Detachment Group" is a mechanical or physical weathering group has been found to effect the stone building materials at Sabratha monuments. Fifteen individual weathering forms were investigated and found to affect the overall area of study with slightly varied degrees of damage intensities ranges (varied between 0 and 3 categories). Weathering agents that act to produce damages on this group are most likely include, the diurnal and seasonal temperature variations; relative humidity fluctuations; salt crystallization; moisture and or water content and to some extent freezing and thawing cycles (when the temperature has lowered to degrees close to zero). The slight differences in the degree of damage intensities is resulted due to differences in the degree of resistivity of stone building materials to weathering agents and the overall original texture of those stones as well.

6. Recommendations

We recommend through this research the Libyan Tourist Agency or the authorities who are in responsibility to take action to minimize or prevent the continuous damages on the stone building materials at Sabratha monuments due to this types of weathering forms. We also recommend that all other types of weathering forms group-2 "discoloration-deposits" and group-4 "fissures-deformations" to be investigated at the Ancient Sabratha City.

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Annex 1. Explanations of terminology and abbreviations (Modified from Fitzner *et al.*, 2002)

Abbrev./Term.	Definition	Abbrev./Term.	Definition
(F)	Detachment of small, thin stone pieces (flakes) parallel to the stone surface	(G)	Detachment of individual grains or small grain aggregates.
(sf)	Detachment of one layer of flakes parallel to the stone surface.	(Gg)	Detachment of larger grains as individual grains or small grain aggregates (stone grus). Especially on granites.
(mf)	Detachment of a stack of flakes parallel to the stone surface.	(Gp)	Detachment of smallest stone particles (stone powder).
(F-S)	Transitional form between flaking and contour scaling.	(GF)	Transitional form between granular disintegration and flaking.
(sf-ss)	Transitional form between single flakes and single scale.	(Gsf)	Transitional form between granular disintegration into sand and single flakes.
(mf-ms)	Transitional form between multiple flakes and multiple scales.	(P)	Detachment of larger compact stone pieces of irregular shape.
(F-P)	Transitional form between flaking and crumbly disintegration.	(sp)	Detachment of larger compact stone pieces in the form of splinters.
(sf-c)	Transitional form between single flakes and crumbling.	(c-sp)	Transitional form between crumbling and splintering.
(CS)	Detachment of larger, platy stone pieces parallel to the stone surface, but not following any stone structure.	(P-S)	Transitional form between crumbly disintegration and contour scaling.
(ss)	Detachment of one layer of scales	(c-ss)	Transitional form between crumbling and single scale.
(ms)	Detachment of a stack of scales.	(X)	Detachment of larger stone sheets or plates following the stone structure
(st)	Detachment of mainly thin scales due to tooling of the stone surface.	(ex)	Detachment of larger stone layers (sheets, plates) following any stone structure

Damage intensities Range					
0	1	2	3	4	5
No visible damage	Very slight damage	Slight damage	Moderate damage	Severe damage	Very severe damage