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EXHAUSTIVE CHARACTERIZATION OF MARBLE TO INDUSTRIAL APPLICATIONS: CASE OF MARBLE FROM THE FILFILA DEPOSIT (SKIKDA, NORTHEAST ALGERIA)

The object of this research is deals with the Filfila marble deposit of all types. The examined area is situated in the Filfila massif, a significant section of the Kabyle basement, in the inner region of the Alpine range in northeastern Algeria. Given that it has been mined for many years, this massif is especially notable for the importance of its marble reserves. There are three primary types of marble found in this deposit: mignonette marble, which is prized for its exquisite green tones; gray marble, which has delicate subtleties; and white marble, which is highly sought after due to its extreme purity.

Multi-scale petrographic techniques that integrate microscopic examinations with macroscopic observations (color, texture, and structure) form the basis of the methodology employed in this work. Under plane-polarized light, thin sections of 30 µm in thickness were created in the University of Annaba's geology lab. According to the results, the material had a uniformly large texture and was primarily composed of microcrystalline calcite. Carefully polished samples were subjected to scanning electron microscopy (SEM) analysis in order to advance the investigation. SEM was able to disclose fine microstructural characteristics, such as crystal shape, microcracks, porosity, and the distribution of mineral phases, because of its nanometric resolution, which shows a high purity of white marble in addition to the main impurities of gray marble. The mechanical characteristics and durability of the marbles were illuminated by these observations, which allowed for the identification of notable variations among them, especially with regard to the density of discontinuities and the size of the crystal grains. By combining optical and electron microscopy techniques, this integrated approach made it possible to thoroughly characterize Filfila marble by exposing its physical characteristics and mineralogical composition. The results offer a solid scientific basis for possible industrial uses and are useful reference information for upcoming comparative geological studies.

Keywords: *marble, Filfila deposit, petrographic, scanning electron microscopy, Energy-Dispersive Spectrometry (EDS).*

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1. Introduction

Marble is a distinguished metamorphic rock that has been prized since antiquity for its extraordinary properties, including its outstanding density, excellent mechanical strength, and unique brilliance that allows it to reflect light with unparalleled elegance. It was created by recrystallizing limestone under extreme heat and pressure. It has a delicate, translucent texture and is frequently dotted with striking veins that are caused by the presence of clays or metallic oxides. Its chromatic richness, which ranges from the deep tones of Belgian black marble to the pure radiance of Carrara's white marble, makes it a timeless material and a universal representation of elegance and sophistication [1, 2].

The research area is situated in the core region of the Alpine chain in northeastern Algeria, within the Filfila Massif. This massif is part of the Kabyle basement and is well known across the world for its excellent marble resources that have been mined for many generations [3]. There are three primary types of marble: Reseda marble with greenish reflections that are highly prized in ornamentation, white marble, and gray marble with subtle tones. Based on an integrated petrographic method, the investigation verifies the metamorphic origin and unique features of thin sections by combining microscopic exams and macroscopic views of the sections under polarized light. This study advances our knowledge of the region's geological formations and creates opportunities for more sensible use of these vast mineral resources [4, 5].

A scanning electron microscope (SEM) was used to do a thorough investigation on meticulously prepared Filfila marble samples in order to enhance this study. This tool's exceptional nanometric resolution allowed it to highlight important microstructural characteristics such porosity, the distribution and existence of microcracks, crystal shape, and the arrangement of mineral phases. Significant differences in marble varieties were found based on the observations, especially with regard to the density of discontinuities and the size of the crystal grains, which have an impact on the mechanical and physical characteristics of the marble. Thus, the integration of SEM and optical imaging offers a strong basis for upcoming practical applications and comparative research [6]. By reviewing the existing scientific literature concerning the Filfila marble deposit it is found that several researches remain relatively limited and present less important information. In particular, previous investigations have not offered a thorough petrographic characterization that connects the mineralogical attributes of the marble with its physical and decorative qualities. Similarly, there is a noticeable absence of studies that systematically evaluate its industrial potential, especially in terms of

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suitability for construction and ornamental purposes. Moreover, issues related to the environmental and economic implications of exploiting this deposit have been largely overlooked in the available works.

The aim of research is to describe the different marble and its characteristics. According to the findings, there are two types of crystalline marble: white marbles and light gray marbles. The light grey marbles are made up of interbedded dolomitic beds that range in thickness from 0.2 to 0.7 m and crystalline rocks with dark grey patches that are 1–2 m. Accordingly, the industrial capacity of different types of Filfila marble can be determined according to their complete properties.

2. Materials and Methods

2.1. Description of the studied element

2.1.1. Location and geographical context of the deposit

The Filfila deposit is located at the northeastern of Algeria, east of the city of Skikda, within a region characterized by rugged terrain. The quarry, which has been in operation for several decades, lies approximately 25 km from the city center of Skikda, commune of Filfila (Fig. 1).

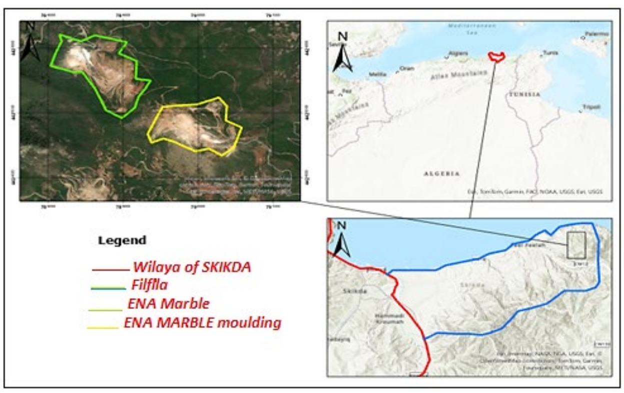


Fig. 1. Geographical location of the Filfila marble quarry

2.1.2. Regional geology

The Filfila deposit is situated within the small Kabylian massif in northeastern Algeria, east of the city of Skikda. Because to the erosion of the Kabyle basement, it emerges as a tectonic window. This exceptional deposit (Fig. 2) was formed as a result of contact metamorphism brought on by the intrusion of granitic masses within the carbonate strata of the Lias during the Langhian.

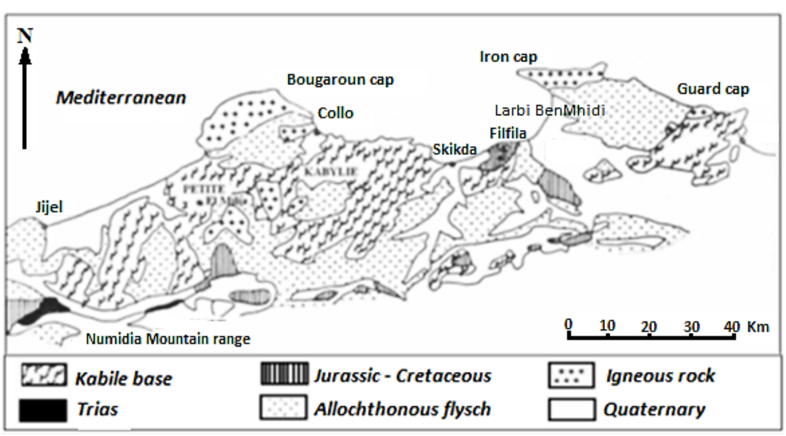


Fig. 2. Regional geological map and location of the Filfila deposit [7]

2.1.3. Geology of the deposit

Djebel Filfila is characterized by a series of metamorphosed argillaceous, sandstone, and limestone rocks. Within this series, several lenticular bodies of pure limestone are present. The second most prominent geological feature is the presence of two large tourmaline granite massifs, located on the NE-SW flanks of Djebel Filfila. On both sides of these granites, contact formations appear. To the east and south of Djebel Filfila, sericite schists and mica schists are found, containing several quartz veins underlying a series of sandy argillaceous rocks, assumed to be of Upper Eocene age. Near the seashore, along the coast, strongly folded quartz schists of Albo-Aptian age can be observed. The western part of the Filfila massif is covered by extensive accumulations of sand dunes [8].

2.1.4. Local geology

Stratigraphy. A detrital series is linked to a mostly carbonate succession in the Filfila area's geologic column. The Lias formations contain the majority of the exploited marbles. A complicated sedimentary and tectonic history is reflected in this geological structure's division into three major tectonic units: the Upper Unit (southern sector), the Middle Unit (central sector), and the Lower Unit (northeastern sector). Major tectonic contacts, denoted by fully developed breccia and microbreccia zones, which show substantial crustal motions and strong fracture activity, divide these three structural groupings [9].

Lower Complex. The sequence begins with microcrystalline marbles that can grow up to 40 meters thick and rest on black argillaceous marl shales that are crisscrossed by veins of siderite, hematite, and quartz. Because of the presence of metallic oxides, the upper part of these marbles exhibits a pinkish tinge with chromatic variations. Conglomerates about 0.5 meters thick are seen upstream. These consist of extremely fractured, coarse-grained white marbles with greenish clay of secondary origin filling the spaces between. These conglomerates are covered with light grey dolomitized marbles that range in thickness between 5 to 7 meters and are interrupted by fissures filled with calcite [10].

A series of bituminous black and dark grey marbles with a highly crystalline texture that range in thickness from 2.0 to 4.5 meters can be found in the upper portion of the geological sector. Light gray facies alternate with huge, uniform saccharoid white marbles as these layers progressively change. The rocks have a microcrystalline structure and a high percentage of calcite (usually 95 to 98%). Outcrops of very pure white marbles with uniform grain sizes and a nearly monomineral composition where calcite makes up 99% of the composition can be found in the northern portion of the quarry [11, 12].

Middle Complex. The Middle Complex, which makes up the quarry's northwest section, is distinguished by a diverse lithological assemblage that exhibits a high degree of geological variability. Actinolite-rich skarns, a core unit of white crystalline marbles, and an upper succession of marly clays with lenses of green limestone make up the stratigraphic sequence from base to top [13].

Actinolite skarns at the base. The contact between the middle and lower units is indicated by a tectonic breccia formed by the skarns. This shear zone has a 20 to 30° drop toward the southwest and is aligned northeast-southwest. They are between 0.5 and 35 meters thick. Gray-blue calcite-rich zones are commonly seen. Though they can locally become schistose, especially when paired with crystalline marble, the skarns typically have a huge texture.

Crystalline marbles. There are two types of crystalline marble: white marbles and light gray marbles. The light grey marbles are made up of interbedded dolomitic beds that range in thickness from 0.2 to 0.7 m and crystalline rocks with dark grey patches that are 1 to 2 m thick. Along bedding planes and cracks, pyrite and mica impregnations are frequently observed. The homogeneous, microcrystalline, massive to slightly bedded white marbles have layer thicknesses ranging from 0.5 to 1.5 meters and may contain dolomite lenses [13].

Marly Clays. The outcrop of these rocks is noted in the eastern part. It is represented by an alternation of marly clay shales partially silicified with marly limestones and sandstone. Within this alternation, the development of lenses of crystalline limestone, partially silicified and of light green color, is noted. The green color is due to the presence of mica impregnations within the limestones [14, 15].

Upper Complex. In this complex, the following units can be observed: grey-blue microcrystalline marbles at the base; white microcrystalline marbles in the middle part; whitish-grey marbles in the upper part. The contact between the upper and middle complexes lies along the reverse fault, while that of the lower complex is located along the overthrust plane, which dips eastward at an angle of 40° to 60° (Fig. 3) [16].

Deposit Structure. The outcrops in the Filfila marble deposit range in width from 100 to 300 meters and can reach a maximum length of 1,100 meters. A lenticular unit with a strike length of 550 m and a lateral extent from 150 to 250 m makes up the economically viable zone. The monoclinal structure of the deposit, which dips northeast at angles between 20° and 40° (NE), is its defining feature [17].

The Filfila marble presents a complex stratigraphic and tectonic composition, represented by Lower, Middle, and Upper units that cover different lithologies. The main matters are; microcrystalline and crystalline marbles, skarns, marly clays, and dolomitized facies. These formations include evidence of intense tectonic deformation, manifested in brecciation, fracturing, and faulted contacts. Within this context, high-purity calcite marbles with considerable decorative value occur. The economically exploitable body forms a lenticular monoclinal structure, measuring approximately 1,100 m in length and 300 m in width, with a northeastward dip of 20–40°.

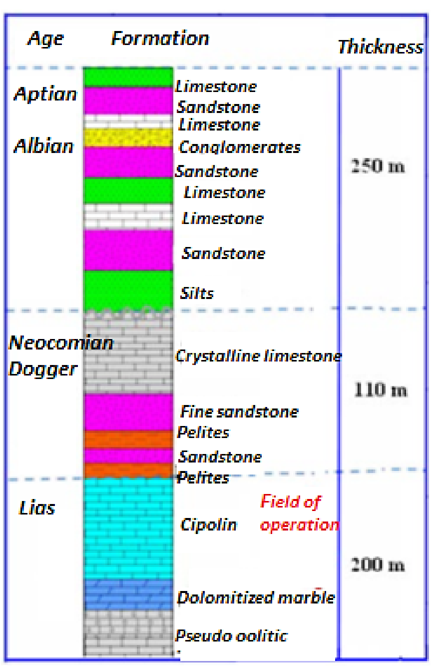


Fig. 3. Stratigraphic column of Filfila massif

2.2. Petrographic study

Petrographic analysis enables precise characterization of the mineralogical composition and texture of rocks in order to determine their origin, evolution, and the geological processes involved. It provides essential data on their formation, transformation, and tectono-metamorphic or magmatic history. This analysis aims in particular to detect and identify the minerals present through their specific characteristics (color, shape, cleavage, etc.). The marble's purity, homogeneity, and other properties were examined to determine potential applications, while its structures and mineral interactions were analyzed within their geological formations, providing insights into the broader geological evolution and resource potential of the Filfila region [18].

A detailed analysis was carried out on these samples at the macroscopic and microscopic scale, with the aim of precisely characterizing the texture and mineralogical composition specific to each variety of marble (Fig. 4).

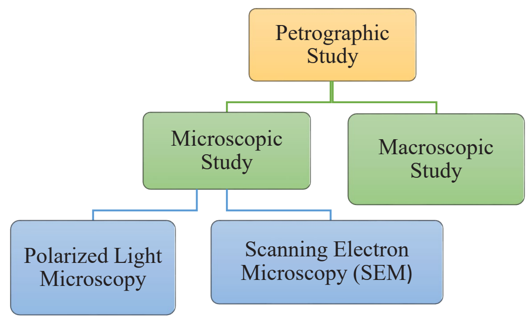


Fig. 4. Illustrating diagram of the petrographic methods study the used

2.3. Macroscopic analysis

When marble, like that from Filfila, is examined macroscopically, its characteristics that are discernible to the unaided eye or with a hand lens are noted and described. This preliminary examination offers basic features that are necessary before moving on to more complex studies like microscopy. It emphasizes the overall look, which includes the sample's dominant hue and any tonal variations (such as white, grey, beige, or vein colors). Grain size, type, or shape variations that reflect the kind of rock and formation processes are used to determine if the texture is homogeneous or heterogeneous.

2.4. Polarized light microscopic analysis

Using polarized light microscopy (PLM), the rocks (the marble) were petrographically examined. At the microscopic level, this technique makes it possible to identify the individual minerals, see textures, and characterize internal structures and rock fabric. It enables the determination of optical characteristics (such birefringence and extinction) to verify mineral identification, the identification of the marble's mineral phases, and the investigation of textures and microstructures to comprehend formation and development mechanisms. In the Annaba University geology lab, thin sections were made according to French norms (about 30 microns thick), with two sections made for each sample for polarized light analysis.

2.5. SEM analysis

The morphology and structure of mineral surfaces can be thoroughly examined through high-resolution imaging provided by scanning electron microscopy (SEM), which is based on electron-matter interactions. This method is used to characterize microstructural features like inclusions, fractures, mineral zones, and textural variations; to ascertain the chemical composition of marble minerals using energy-dispersive spectroscopy (EDS); and to investigate the microstructure, texture, and interrelationships between mineral phases.

3. Results and Discussions

3.1. Sample 01: white marble

3.1.1. Macroscopic study

As seen in Fig. 5, the macroscopic analysis of the Filfila marble reveals that the sample is white in color, homogenous in appearance, and huge in texture. These characteristics of this kind of marble are reflected in its homogeneity and compact structure.

Fig. 5. Sample of white marble

3.1.2. Microscopic study

The microscopic analysis shows that the marble sample is petrographically a microcrystalline limestone, with a microcrystalline structure composed almost entirely of calcite (close to 100%), indicating a nearly monomineralic composition. It corresponds to a white crystalline limestone characterized by small, equigranular calcite crystals and remarkable mineralogical homogeneity. These features confirm both the purity and the microcrystalline nature of the studied marble (Fig. 6).

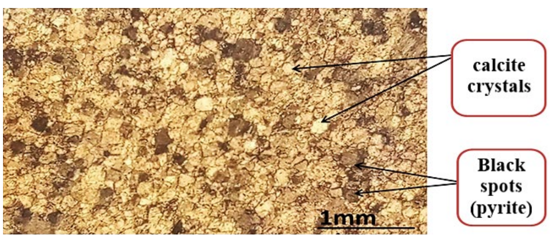


Fig. 6. Polarized light photograph of the white marble of Filfila (LP). 5× lens

3.2. Sample 02: Dark gray marble

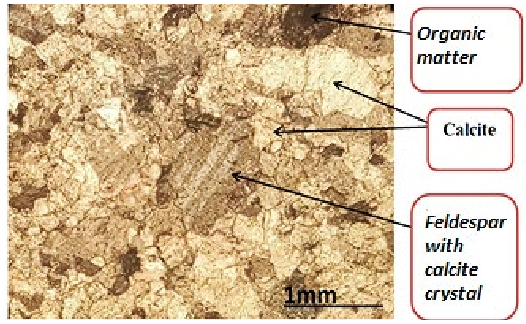
3.2.1. Macroscopic study

The dark grey marble sample from the Filfila deposit has a huge texture, a non-homogeneous appearance, and a dark grey coloring when seen macroscopically (Fig. 7). These features point to a dense and compact structure that is in line with the material's lithological nature.

Fig. 7. Sample of dark gray marble

3.2.2. Microscopic study

The petrographic study shows that the dark grey marble is a crystallophyllian limestone composed mainly of recrystallized calcite, with coarser grains than those of the white marble. The microcrystalline structure includes minor components such as organic matter, iron oxide grains, mica, feldspar, and quartz (Fig. 7, Fig. 8). Chemically, the composition is approximately 87% calcite, 7–8% organic matter, 1% iron oxide, 2% mica, 1% feldspar, and 2% quartz. The presence of black (iron oxide) and green (mica) spots, as well as feldspar and quartz, reflects contact metamorphism with twinned calcite crystals.



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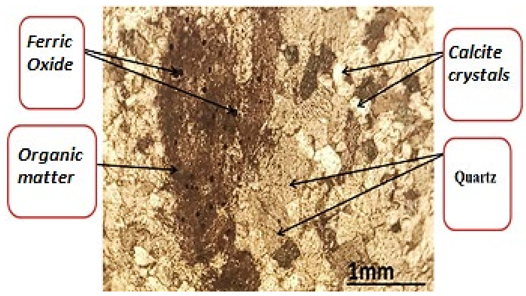

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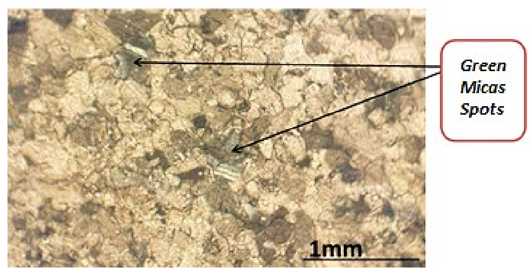


c

Fig. 8. Polarized light photograph of dark gray marble from Filfila (LP), 5× lens: *a* – marble with feldspar and calcite; *b* – marble with calcite and quartz; *c* – marble with green mica

Microscopic observation of the gray Filfila marble reveals a heterogeneous mineral composition. It is composed of organic matter and iron oxides, testifying to an alteration process. This reveals a complex petrographic evolution of the rock, which reflect its sedimentary origin and subsequent metamorphic transformations.

3.3. Sample 03: Reseda marble

3.3.1. Macroscopic study

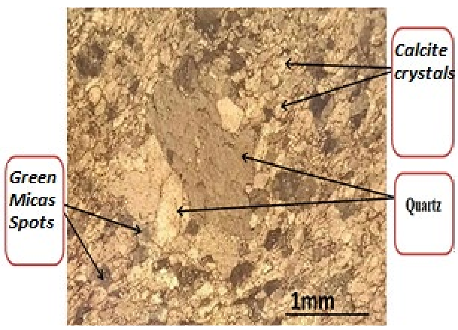
According to the macroscopic analysis, the third marble sample has a huge texture, a non-homogeneous appearance, and a Reseda green color, as shown in Fig. 9. These characteristics draw attention to its irregular and compact structure.

Fig. 9. Sample of Reseda marble

3.3.2. Microscopic study

Microscopic analysis shows that the marble is a microcrystalline limestone with a microcrystalline structure. Its chemical composition consists of approximately 93% calcite, 3% quartz, 2% mica, and 2% feldspar. The rock is intersected by small green veins, with feldspar and minor amounts of mica present throughout the matrix. Isolated quartz crystals are also observed, indicating the influence of contact metamorphism. These mineralogical and structural features, as illustrated in Fig. 10, reflect the complex formation history and mineral associations within the studied sample.

Microscopic examination of Reseda Filfila marble reveals the presence of patches of green mica and calcite crystals dominating the matrix, accompanied by grains of quartz and feldspar. This mineralogical association testifies to the complex petrographic evolution of the rock and its sedimentary origin.



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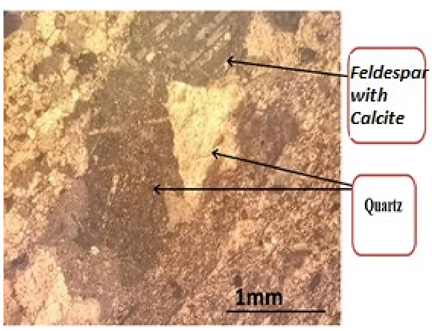


b

Fig. 10. Polarized light photograph of Reseda marble from Filfila (LP), 5× lens: *a* – marble with green mica and quartz; *b* – marble with feldspar and quartz

3.4. Analysis by scanning electron microscopy and energy dispersive spectrometry (SEM/EDS)

3.4.1. Interpretation of thin sections of with marble

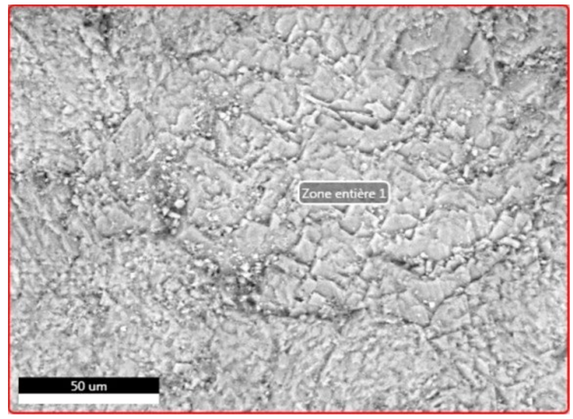
Carbon (C) 15.91%, oxygen (O) 56.66%, sodium (Na) 2.88%, magnesium (Mg) 1.81%, silicon (Si) 0.44%, and calcium (Ca) 22.31% were the elements in the sample that could be quantified using scanning electron microscopy mixed with energy-dispersive spectrometry (SEM-EDS), as shown in Table 1.

Table 1

EDS Analysis of the thin section image of white marble

Element	Mass %	Atomic %	Total intensity	Error	K_{ratio}	*Z*	*A*	*F*
C K	15.91	23.50	157.04	8.40	0.0677	1.0707	0.3976	1.0000
O K	56.66	62.82	591.76	10.16	0.0784	1.0253	0.1351	1.0000
NaK	2.88	2.22	53.47	12.20	0.0044	0.9318	0.1625	1.0023
MgK	1.81	1.32	68.08	10.82	0.0042	0.9478	0.2445	1.0040
SiK	0.44	0.28	37.07	11.00	0.0021	0.9329	0.4986	1.0126
CaK	22.31	9.87	2147.77	1.74	0.2030	0.8810	1.0258	1.0070
C K	15.91	23.50	157.04	8.40	0.0677	1.0707	0.3976	1.0000

According to these findings, the predominant mineral component is calcite ($CaCO_3$). Petrographic identification of a crystalline limestone is supported by the increased mass percentages of carbon, calcium, and oxygen, which are all in line with the chemical makeup of calcite (Fig. 11).



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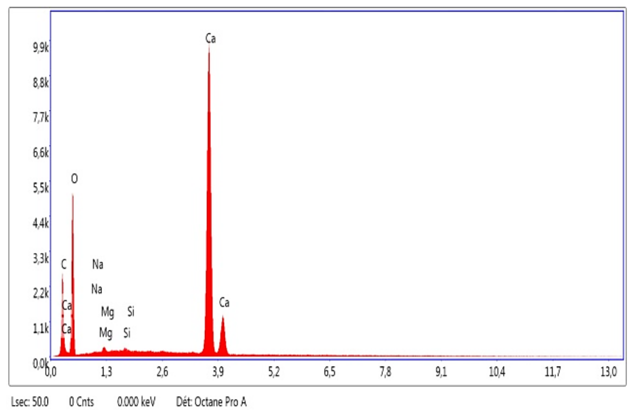

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Fig. 11. Elemental analysis of the white marble using EDS: *a* – white marble area analyzed; *b* – peaks of the predominant chemical elements

3.4.2. Interpretation of thin sections of grey marble

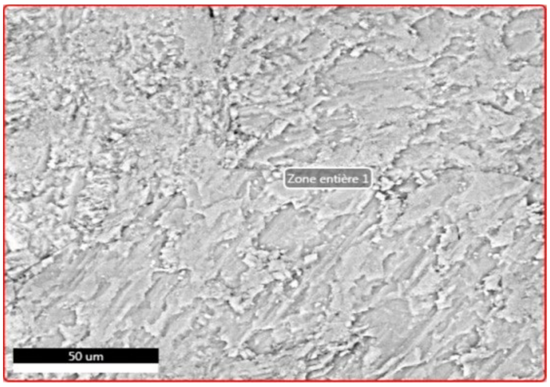
Carbon (C) 13.42%, oxygen (O) 58.52%, sodium (Na) 3.09%, magnesium (Mg) 2.05%, silicon (Si) 0.57%, and calcium (Ca) 22.36% were the elements found in the grey marble according to the analysis done using scanning electron microscopy coupled with energy-dispersive spectrometry (SEM and EDS). These findings support the petrographic data, which showed that the main mineral was calcite ($CaCO_3$) (Table 2).

Table 2

EDS Analysis of the thin section image of grey marble

Element	Mass %	Atomic %	Total intensity	Error	K_{ratio}	*Z*	*A*	*F*
C K	13.42	20.05	131.63	8.69	0.0557	1.0726	0.3870	1.0000
O K	58.52	65.65	649.11	10.08	0.0840	1.0271	0.1398	1.0000
NaK	3.09	2.41	58.10	12.09	0.0046	0.9335	0.1576	1.0023
MgK	2.05	1.51	77.78	10.57	0.0046	0.9496	0.2355	1.0039
SiK	0.57	0.36	49.05	9.12	0.0026	0.9347	0.4810	1.0123
CaK	22.36	10.01	2285.64	1.69	0.2031	0.8827	1.0225	1.0070
C K	13.42	20.05	131.63	8.69	0.0557	1.0726	0.3870	1.0000

High levels of carbon, oxygen, and calcium show that recrystallized calcite is more common. Significant concentrations of magnesium and sodium point to the existence of accessory minerals like dolomite and sodic feldspars, particularly albite. In agreement with petrographic studies, the presence of silicon, albeit in trace amounts, suggests the presence of quartz and feldspar components. All in all, these outcomes are consistent with the conclusions drawn from the thin section's petrographic examination in Fig. 12.



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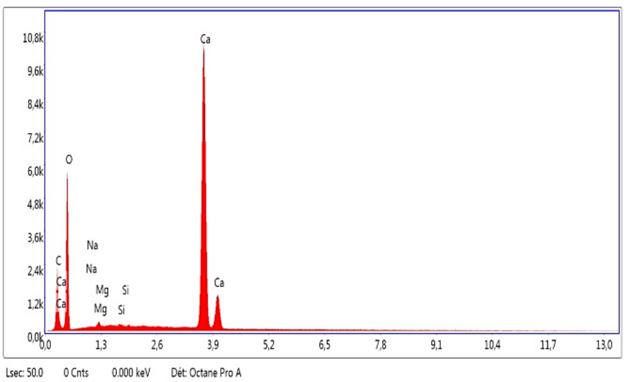


b

Fig. 12. Elemental analysis of the grey marble using EDS: *a* – grey marble area analyzed; *b* – peaks of the predominant chemical elements

3.4.3. Interpretation of thin sections of Reseda marble

The image's microcrystalline structure is consistent with a texture made up of tiny calcite grains, which is typical of marbles that have undergone metamorphism. The advanced recrystallization of calcium carbonate is shown in this uniform microstructure. Dark veinlets indicate element redistribution and mineralogical reorganization during metamorphism, which is probably related to fluid inflow or regional temperature and pressure changes. Chemical investigation employing energy-dispersive spectrometry (EDS) has revealed that calcite ($CaCO_3$) is the primary mineral phase. Table 3 indicates considerable levels of calcium (23.58%), oxygen (57.45%), and carbon (13.30%). Silicate minerals, such as quartz and feldspars (particularly albite), are present in silicon (0.52%), aluminum (0.72%), and sodium (2.45%). These minerals were most likely generated from clay impurities in the original limestone protolith. Marbles that have undergone contact metamorphosis are usually linked to these phases. Additionally, the existence of micas, such biotite or muscovite, which are frequently found in metamorphosed carbonate deposits, may be the reason for the magnesium level (1.98%).

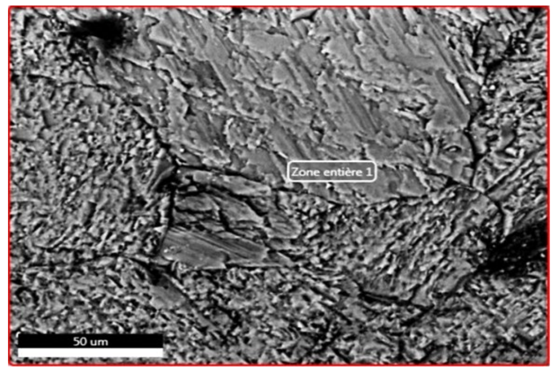
These observations align with the results of the petrographic investigation and are depicted in Fig. 13.

Energy dispersive spectral (EDS) test of the Reseda marble thin section, Table 3, shows the predominance of oxygen (57.45% by mass) and carbon (13.30% by mass), thus confirm the carbonate nature of the rock. These results are consistent with petrographic observations and provide additional evidence for the mineralogical composition of the marble.

Table 3

EDS analysis of the thin section image of Reseda marble

Element	Mass %	Atomic %	Total intensity	Error	K_{ratio}	*Z*	*A*	*F*
C K	13.30	20.07	134.42	8.74	0.0542	1.0744	0.3795	1.0000
O K	57.45	65.05	640.44	10.12	0.0804	1.0290	0.1360	1.0000
NaK	2.45	1.93	48.28	12.25	0.0039	0.9353	0.1673	1.0025
MgK	1.98	1.47	79.39	10.70	0.0048	0.9514	0.2555	1.0042
SiK	0.72	0.48	42.94	11.40	0.0024	0.9163	0.3678	1.0075
CaK	0.52	0.34	45.41	9.86	0.0025	0.9365	0.5055	1.0126
C K	23.58	10.66	2224.08	1.65	0.2137	0.8845	1.0183	1.0066



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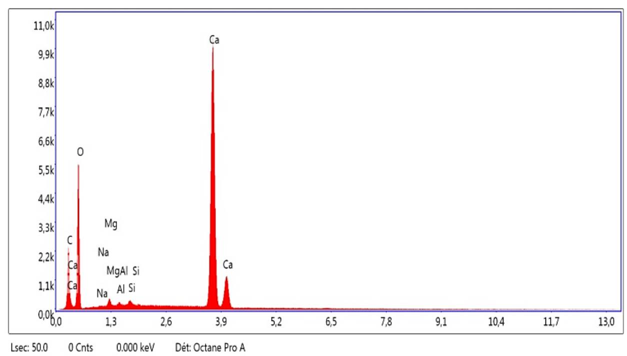

b

Fig. 13. Elemental analysis of Reseda marble using EDS: *a* – Reseda marble area analyzed; *b* – peaks of the predominant chemical elements

3.5. Elemental mapping of the polished section

3.5.1. Elemental mapping of the polished section of white marble

The elemental study performed using EDS mapping on the polished section of white marble reveals a homogeneous and regular distribution of elements inside the rock matrix. The high amounts of carbon (C) and oxygen (O), which appear yellow and light orange, respectively, suggest a significant amount of carbonate, primarily in the form of calcite, the primary mineral component of marble. The presence of magnesium (Mg), shown in red, indicates secondary alteration or mineralogical transformation processes and suggests a partial dolomitization of the rock. Additionally, the discovery of silicon (Si) in violet and aluminum (Al) in light blue indicates that aluminosilicate minerals-likely quartz and feldspars-that were created from clay impurities in the original limestone made a little but noteworthy contribution (Table 4).

This dark orange picture of calcium (Ca) further supports the impression of a calcareous marble. Chlorine (Cl) may be linked to residual fluid inclusions or auxiliary minerals even though its concentration is only 1% (in blue). The finding of sodium (Na) in light blue is consistent with the presence of sodic feldspars such as albite. These results are supported by quantitative EDS data, which show a composition that is mostly carbonate and enriched in calcite with significant amounts of dolomite, quartz, and feldspars. These results are completely congruent with the petrographic investigation (Fig. 14).

Table 4

EDS analysis of the elemental map of the polished section of white marble

Element	Mass %	Atomic %	Total intensity	Error	K_{ratio}	Z	A	F
C K	18.09	25.71	134.00	9.86	0.0719	1.0641	0.3736	1.0000
O K	57.84	61.72	581.10	9.77	0.0943	1.0186	0.1601	1.0000
NaK	3.57	2.65	56.30	11.48	0.0046	0.9253	0.1402	1.0023
MgK	2.58	1.81	80.70	10.47	0.0047	0.9411	0.1944	1.0036
SiK	1.56	0.99	73.70	9.84	0.0038	0.9063	0.2680	1.0058
CaK	0.71	0.43	51.40	9.21	0.0024	0.9262	0.3691	1.0094
C K	0.18	0.09	23.30	10.55	0.0012	0.8628	0.7760	1.0420

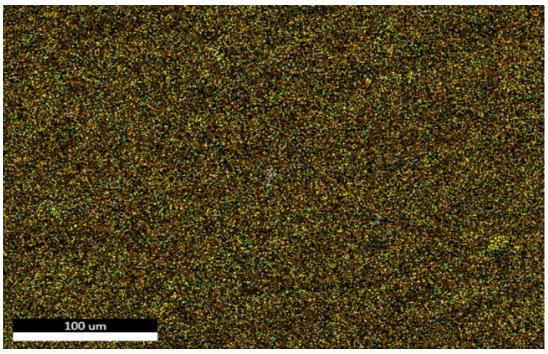

Fig. 14. Elemental mapping of the polished section of white marble

3.5.2. Elemental mapping of the polished section of grey marble

Energy-dispersive spectroscopy (EDS) elemental mapping on the polished piece of grey marble reveals a highly consistent spatial distribution of the primary chemical elements inside the rock matrix. It is confirmed that calcite ($CaCO_3$) is the major mineral phase by the regular and uniform distribution of calcium (Ca), which accounts for approximately 55% of the total composition. Oxygen (O), which makes up around 24 percent of the total mass, is present in carbonate minerals like calcite and dolomite and has a distribution pattern similar to that of calcium. The presence of magnesium (Mg), which accounts for around 5% of the composition and clearly suggests partial dolomitization of the original limestone, indicates the creation of dolomite ($CaMg(CO_3)_2$) as a subsequent phase (Fig. 15).

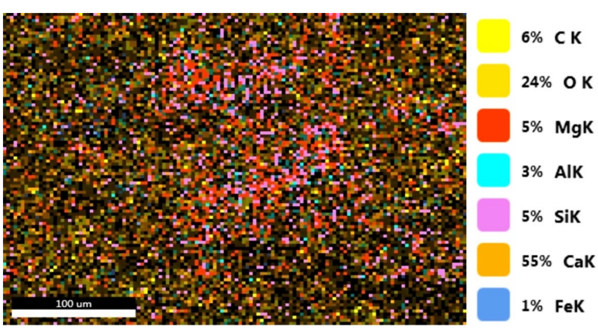

Fig. 15. Elemental mapping of the polished section of grey marble

The existence of accessory aluminosilicate minerals, most likely plagioclase feldspars and sheet silicates like muscovite or biotite, is indicated by trace amounts of silicon (Si) and aluminum (Al). These minerals, which reflect the original sedimentary impurities or fluid induced metasomatic changes, are frequently found in marbles that have undergone contact or regional metamorphism. Very little iron (Fe) is found (about 1%), either as components of ferromagnesian accessory minerals or as finely distributed iron oxides. Calcite and dolomite make up the majority of the recrystallized grey marble, with silicate and iron-bearing phases contributing a secondary amount, according to the overall geochemical signature obtained by EDS mapping. These results are in good agreement with petrographic findings. Table 5 shows how this elemental distribution offers important information about the marble's metamorphic history and mineralogical evolution.

Table 5

EDS analysis of the elemental map of the polished section of grey marble

Element	Mass %	Atomic %	Total intensity	Error	K_{ratio}	Z	A	F
C K	7.71	12.39	78.50	12.46	0.0299	1.0853	0.3574	1.0000
O K	57.40	69.30	666.80	10.69	0.0951	1.0399	0.1593	1.0000
NaK	3.03	2.41	126.00	11.08	0.0120	0.9621	0.4094	1.0048
MgK	1.29	0.93	69.30	13.65	0.0065	0.9267	0.5377	1.0083
SiK	1.45	1.00	97.80	11.20	0.0093	0.9472	0.6661	1.0133
CaK	28.66	13.81	1375.10	2.19	0.2588	0.8950	1.0029	1.0057
C K	0.45	0.16	11.60	55.13	0.0037	0.7984	0.9837	1.0426

3.5.3. Elemental mapping of the polished section of Reseda marble

Major elements are uniformly distributed throughout the rock matrix, according to elemental mapping done on the Reseda marble sample using energy-dispersive spectrometry (EDS). It is evident that calcite ($CaCO_3$), the main mineral phase of the marble, predominates among the most abundant components, which are oxygen (57.43%) and calcium (27.11%). The rock's substantial carbonate content is further supported by the presence of carbon (10.96%) and magnesium (1.49%), which indicate the presence of dolomite ($CaMg(CO_3)_2$) as a secondary mineral that was created by partial dolomitization of the original limestone.

Aluminum (0.60%), silicon (0.54%), and sodium (1.86%) traces point to the presence of accessory aluminosilicate minerals, which most likely include plagioclase feldspars and sheet silicates like biotite or muscovite. These elements could be the result of mineral phases added during contact metamorphism or detrital contaminants in the protolith. The uniformity of the metamorphic processes involved is reflected in the silicates' uniform distribution throughout the matrix, despite their low quantities (Table 6).

Table 6

EDS analysis of the elemental map of the polished section of grey marble

Element	Mass %	Atomic %	Total intensity	Error	K_{ratio}	Z	A	F
C K	10.96	17.02	104.30	8.53	0.0452	1.0793	0.3822	1.0000
O K	57.43	66.94	560.20	10.05	0.0793	1.0340	0.1335	1.0000
NaK	1.86	1.51	33.40	12.42	0.0033	0.9400	0.1878	1.0026
MgK	1.49	1.14	54.60	10.24	0.0042	0.9563	0.2924	1.0045
SiK	0.60	0.41	31.90	10.49	0.0023	0.9210	0.4204	1.0082
Ca K	0.54	0.36	40.40	8.83	0.0029	0.9414	0.5632	1.0139
C K	27.11	12.61	1859.20	1.55	0.2460	0.8893	1.0145	1.0057

Petrographic observations, which characterize a recrystallized, fine-grained texture dominated by calcite with small inclusions of dolomite and ancillary silicate minerals, are compatible with the homogeneous element's distribution seen in the EDS maps. The sample's homogeneity and overall mineralogical composition highlight the

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Reseda marble's structural consistency and geochemical stability. These qualities increase the marble's worth for both beautiful stonework and industrial uses (such as building or as a raw material for making lime). Fig. 16 provides visual support for these findings.

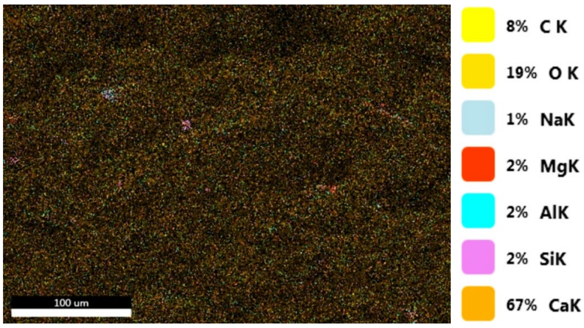

Fig. 16. Elemental mapping of the polished section of Reseda marble

The energy dispersive X-ray spectroscopy (EDS) results shows that carbon and oxygen are the predominant elements in the grey marble, which indicate its carbonate nature with a predominance of calcite. In addition, minor quantities of sodium, magnesium, silicon, and calcium were found, let's also note the presence of some additional minerals. These findings confirm that the Filfila marble is essentially the carbonated nature, while also highlighting slight geochemical variations that may influence its petrographic characteristics and potential applications in industrial and decorative contexts.

The results of this petrographic and geological study of the Filfila marble mine demonstrate considerable practical importance. They allow for the classification of the mineral and structural properties of marble and the determination of its suitability for industrial and decorative uses. The predominantly calcareous nature of this marble gives it physical and aesthetic properties that make it ideal for the manufacture of luxury building materials, architectural facade cladding, and the production of value-added decorative stones. Marble powder can also be used in the cosmetics industry and as an additive in poultry feed.

These data can also help guide mining investment strategies and ensure rational resource exploitation, in accordance with local and international market requirements. Despite the precision of the petrographic analyses and microscopic observations, the study remains limited in terms of the completeness of the representative samples of the entire mining reserve. Furthermore, the physicomechanical tests and environmental assessment associated with the extraction and mining processes were not addressed in depth, which could limit the direct application of the results in the absence of additional data. Therefore, the current results should be considered preliminary conclusions requiring more detailed experimental and field analyses. This study paves the way for further research on the mechanical strength properties of marble, its environmental impacts during cutting and polishing processes, as well as the potential for improving mining techniques to increase productivity and reduce deformation during extraction and transportation. It would also be wise to broaden the economic dimension by comparing the properties of Filfila marble with those of other national and international types, in order to determine its competitive position in the global marble market.

4. Conclusions

The Filfila marble deposit, located in the rough, high-relief terrain (> 580 m) of Northern Algeria's Alpine folded domain-more precisely, the small Kabylie parautochthonous block is described in this paper along with its geology and petrography. The deposit is located in the Filfila parautochthon, which is made up of Miocene granitic outcrops and Jurassic-Cretaceous terrains that have been overthrown by Lower Paleozoic series. The commercial marble and skarns were produced by contact metamorphism fueled by granite intrusions, and the marble is locally connected with Lower Lias (Mesozoic) formations that include brachiopod limestones and dolomitic beds.

According to mineralogy, the marble is a homogenous metamorphic limestone with a microcrystalline structure and a huge texture that is dominated by calcite. Significant variety is revealed by petrographic examination of the white, grey, and Reseda varieties:

White marble. High purity, uniform texture, and a preponderance of fine-grained calcite are characteristics that point to high grade contact or regional metamorphism with few impurities.

Grey marble. Exhibits a range of cementation and grain sizes, which reflects different diagenetic circumstances. The existence of feldspars and supplementary quartz suggests a more intricate sedimentary protolith.

Reseda marble. has a microcrystalline structure that is consistent with low to medium grade metamorphism and a preponderance of calcite with small quartz/feldspar inclusions. Iron oxides and organic debris are the main causes of color differences in all sorts.

Thin section observations were validated and improved by scanning electron microscopy (SEM), which also provided more microstructural information. All of the findings point to a marble suite that is mostly made up of calcite, with micas and feldspar in lower proportions. The thorough microstructural and petrographic characterization provides a crucial basis for the sustainable utilization and reasonable appraisal of the Filfila marble deposits.

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Conflict of interest

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The authors affirm that no artificial intelligence technologies were employed in this work.

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