ISSN: 2331-1959 Volume 7, Number 3, July 2019

Scientific Research Publishing

Archaeological Discovery

ISSN: 2331-1959

www.scirp.org/journal/ad

Journal Editorial Board

ISSN Print: 2331-1959 ISSN Online: 2331-1967
http://www.scirp.org/journal/ad

Archaeological Discovery, 2019, 7, 155-191
http://www.scirp.org/journal/ad
ISSN Online: 2331-1967
ISSN Print: 2331-1959

Table of Contents

Volume 7 Number 3 July 2019

Archaeological Discovery (AD)
Journal Information

SUBSCRIPTIONS

The *Archaeological Discovery* (Online at Scientific Research Publishing, www.SciRP.org) is published quarterly by Scientific Research Publishing, Inc., USA.

Subscription rates:
Print: $39 per issue.
To subscribe, please contact Journals Subscriptions Department, E-mail: sub@scirp.org

SERVICES

Advertisements
Advertisement Sales Department, E-mail: service@scirp.org

Reprints (minimum quantity 100 copies)
Reprints Co-ordinator, Scientific Research Publishing, Inc., USA.
E-mail: sub@scirp.org

COPYRIGHT

PRODUCTION INFORMATION

For manuscripts that have been accepted for publication, please contact:
E-mail: ad@scirp.org

Archaeological Discovery, 2019, 7, 155-191
http://www.scirp.org/journal/ad
ISSN Online: 2331-1967
ISSN Print: 2331-1959

Marine Micro-Remains on Holy Maria-Magdalena's Hair, Studied by Scanning Electron Microscopy and Elemental Analysis

Gérard Lucotte[1*], Eglantine D'Hérissart[1], Thierry Thomasset[2]

[1]Institut d'Anthropologie Moléculaire, Paris, France
[2]Laboratoire d'Analyse Physico-Chimique, UTC de Compiègne, France

Email: *lucotte@hotmail.com

How to cite this paper: Lucotte, G., D'Hérissart, E., & Thomasset, T. (2019). Marine Micro-Remains on Holy Maria-Magdalena's Hair, Studied by Scanning Electron Microscopy and Elemental Analysis. *Archaeological Discovery, 7,* 155-191.
https://doi.org/10.4236/ad.2019.73009

Received: March 26, 2019
Accepted: June 1, 2019
Published: June 4, 2019

Abstract

As a new contribution to the scientific knowledge of Holy Maria-Magdalena's remains, we have studied by SEM-EDX some mineral particles and micro-organism debris adhering to her hair. We found on it mineral particles of gypsum, aragonite and salt, algae fragments, microorganism as diatoms, coccoliths and tintinnides, and micro-debris of Crustaceans. Such marine micro-remains indicate a past close contact of the hair with sea water.

Keywords

Maria-Magdalena's Hair, Marine Mineral Particles, Fragments of Algae, Diatoms, Coccoliths and Tintinnides, Micro-Debris of Crustaceans, SEM-EDX

1. Introduction

Holy Maria-Magdalena (3?-63?), named here Marie-Madeleine, is the most abundantly cited women of the four Gospels. There were some places (notably Palestine) where Marie-Madeleine could be buried. According to the French "tradition des Saints de Provence" (Trouillet, 2016), she (and her companions) landed to the present French Mediterranean shores (in a region corresponding to the current part of Les-Saintes-Maries-de-la-mer) and attained further the towns of Marseilles and Aix-en-Provence (where they evangelized the Provence region).

Some relics (cranium, bones and hairs) of the presumed Marie-Madeleine were kept in the Saint-Maximin basilica, where a large lock of Marie-Madeleine's hair is arranged in a dedicated reliquary. We have obtained some hairs from this lock, for scientific purposes (microscopic examinations, chemical analyses and radio-datation). We have published these last years the mitochondrial DNA haplogroup found by extracting genomic DNA from the bulb of hair number 10 (Lucotte, 2016), the explanation of the brown-red observed colour of the hairs by scanning electron microscopic characterisation of its melanosomes (Lucotte & Thomasset, 2017) and the description of some fennel rests on or at the vicinity of some (numbers 4, 6, 9 and 10) of these hairs (Lucotte et al., 2018).

In the present study, we describe and analyze many sorts of micro-remains of marine origin that were located on the various studied hairs of Marie-Madeleine.

2. Material and Methods

The material is ten of a large lock of Marie-Madeleine's hairs, that were kept in a dedicated reliquary in the Saint-Maximin basilica (Lucotte, 2016). These hairs, numbered 1 to 10, were loaded (see Lucotte, 2016, for a photo showing the sticky-paper where the ten hairs are loaded) on a sterile sticky-paper for SEM examination and EDX analyses. A special characteristic of these hairs id their extreme dryness (Lucotte & Thomasset, 2017); so, when they were loaded (in folding back its) on the sticky paper, most of the relatively voluminous marine micro-remains particles adhering natively to hairs were dropped on the sticky-paper in their immediate neighbouring respective hair environments.

The SEM (Scanning Electron Microscopy) apparatus used for micro-remains observations is the FEI model Quanta FEG (an environmental electron microscope apparatus). Elemental analysis was achieved by using EDX (Energy Dispersive X-Ray spectroscopy), the SEM microscope being equipped with the probe model X-flash 6/30. Both LFD (Large Field Detector) and CBS (Circular Back Scattering) were used, the last one to better detect heavy elements.

Each elemental analysis is given in the form of a spectrum, with kiloelectrons/Volts (ke/V) on the abscissa and elemental peaks heights (cps/eV) in ordinates.

3. Results

Results obtained correspond to marine micro-remains located on hairs numbers 1 to 10, or in their immediate vicinities. We found mineral particles, remains of various microorganisms (Diatoms, Coccoliths and Tintinnids), fragments of algae, and some parts of micro-crustaceans.

3.1. A Marine Island

What we named as a "marine island" is a local concentration of several marine micro-rests on, and at the vicinity, of some hair portion. **Figure 1** shows the marine island located of some portion of hair number 8, and containing at least three sorts of marine micro-remains: a diatom, a gypsum particle and (flooding from the hair portion) two thalle fragments of an algae.

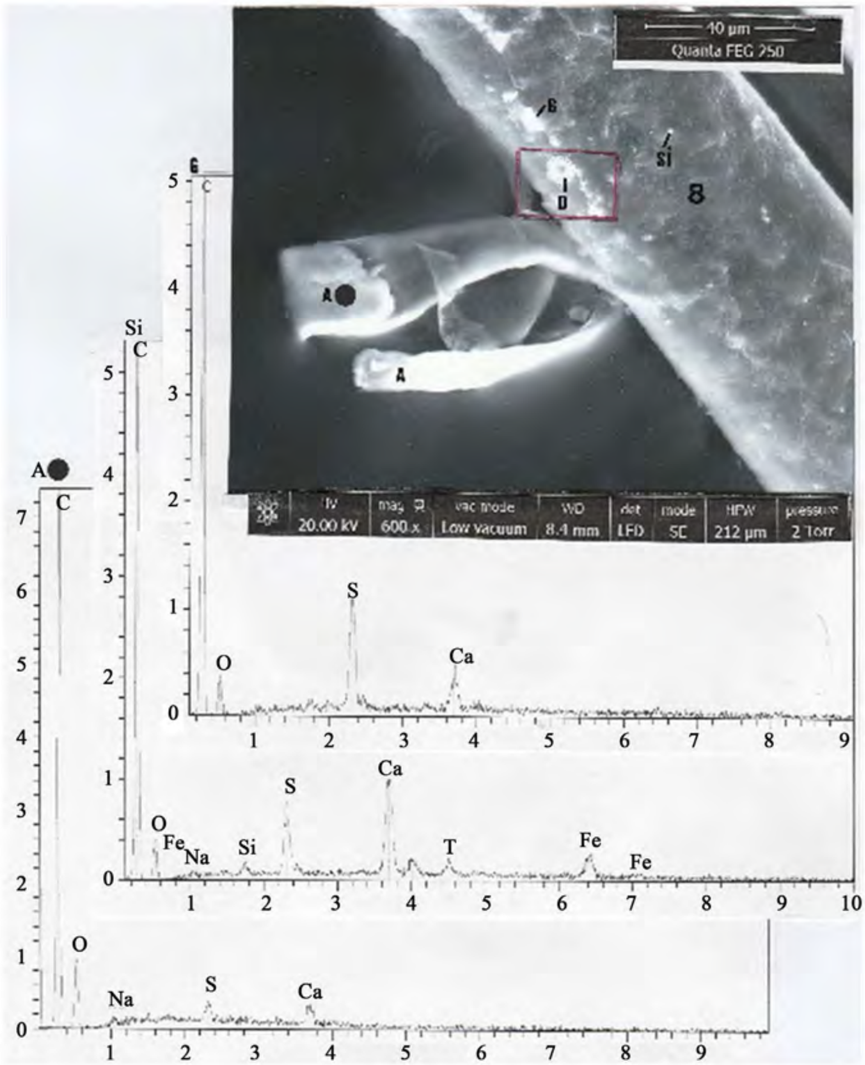


Figure 1. *Above*: a SEM photograph (in LFD, 600×) of the marine island located on hair number **8**. G: a gypsum particle; Si: a silice particle; D: a diatom (the red rectangle area is enlarged in a following figure); A: two parts of the thalle of an algae. The black dot in the algae superior part indicates the location where elemental analyses are realized. *Below*: the spectras. Upper spectrum that of the G particle; medium spectrum: that of the Si particle; lower spectrum: that of the A superior part. C: carbon; O: oxygen; Fe (three peaks): iron; Na: sodium; Si: silicium; S: sulphur; Ca (two peaks): calcium; Ti: titanium.

3.2. Mineral Particles

The SEM photograph of **Figure 2** shows the appearance of the mineral powder covering some part of hair number 1 (the longest). This powder is constituted of two different sorts of micro-particles: that of well shaped forms (as for example the triangular particle number 2, located outside of the hair) and that of the most broadcasted forms (as exemplified in the zone 1 of the photograph) which correspond to the dissolved product.

Spectrum of 2 is characterized by relative high contents of sulphur and calcium. It corresponds, as the G particle of **Figure 1**, to some form of calcium

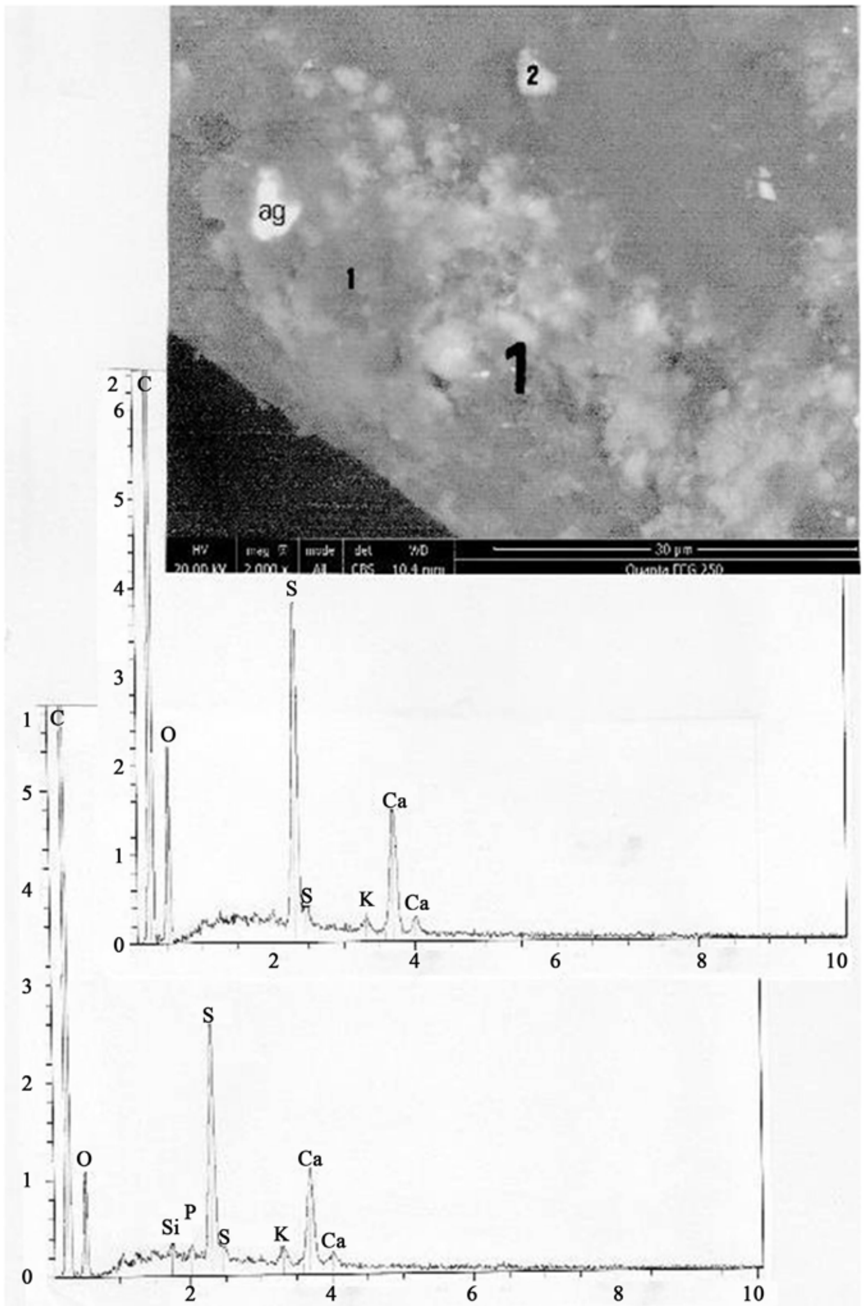


Figure 2. Calcium sulphate on hair number 1. *Above*: SEM photograph (in CBS, 2000×) of a hair number **1** portion (1: some part of the surface of the hair, covered with very fine micro-particles; 2: a mineral particle located outside of the hair surface; Ag: a particle of silver). *Below*: lower spectrum (spectrum of 1). Upper spectrum (*spectrum* of 2). C: carbon; O: oxygen; Si: silicium; P: phosphorous; S (two peaks): sulphur; K: potassium; Ca (two peaks): calcium.

sulphate of the gypsum type ($CaSO_4 \cdot 2H_2O$). Spectrum of 1 (with the same elemental composition of that of 2) corresponds to the anhydrite form ($CaSO_4$).

Most of the hairs contain at least some traces of gypsum deposits at their surfaces. **Figure 3** shows the example of one gypsum deposit on some part of a

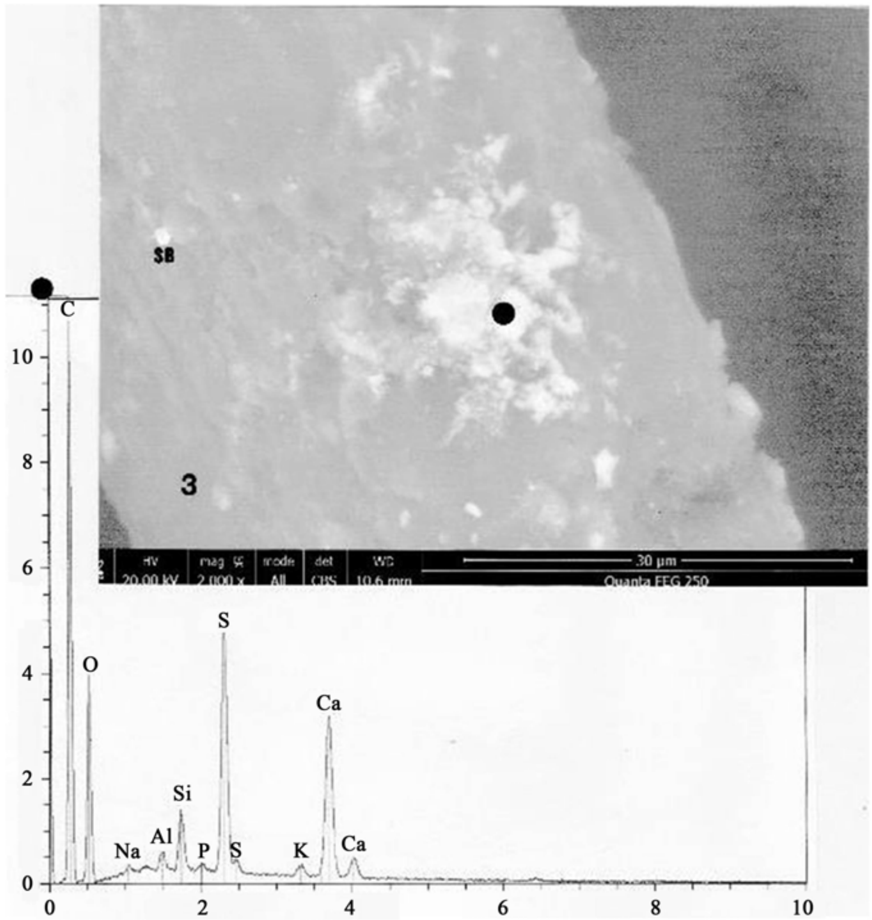


Figure 3. Gypsum pile on hair number **3**. *Above*: SEM photograph (in CBS, 2000×) of a gypsum pile located on hair number **3** portion. The black dot indicates the location where EDX analysis is realized. (SB: a particle of barium sulphate). *Below:* spectrum at the black dot. C: carbon; O: oxygen; Na: sodium; Si: silicium; P: phosphorous; S (two peaks): sulphur; K: potassium; Ca (two peaks): calcium.

portion of hair number 3. Most mineral particles of the deposit had angular outlines, and the global spectrum is that of gypsum.

Figure 4 shows another pile of gypsum crystals, located in another part of hair number 3. Most of the crystals of the pile have very acute outlines (with the characteristic "fer de lance" form), as in gypsum macro-crystals.

But another sort of particles (numbered 1 to 10 on the photograph) of the pile are of some different form (they are smaller, and generally lumped to each other) and aspect in RX (they are less bright to electrons). Their spectras, relatively rich in carbon, oxygene and calcium, are those of a calcium carbonate. It corresponds to some form of aragonite ($CaCO_3$), of the same chemical formulae to that of calcite, but that crystallizes in the orthorhombic system.

Only two particles of salt were found on the hair surfaces. The first one (Figure 5) is a fine powder of salt (ClNa) found at the border of some part of hair number 10. The second, located on some part of hair number 2 surface, is a particle of more than 20 µm of maximal length and with some tormented outlines

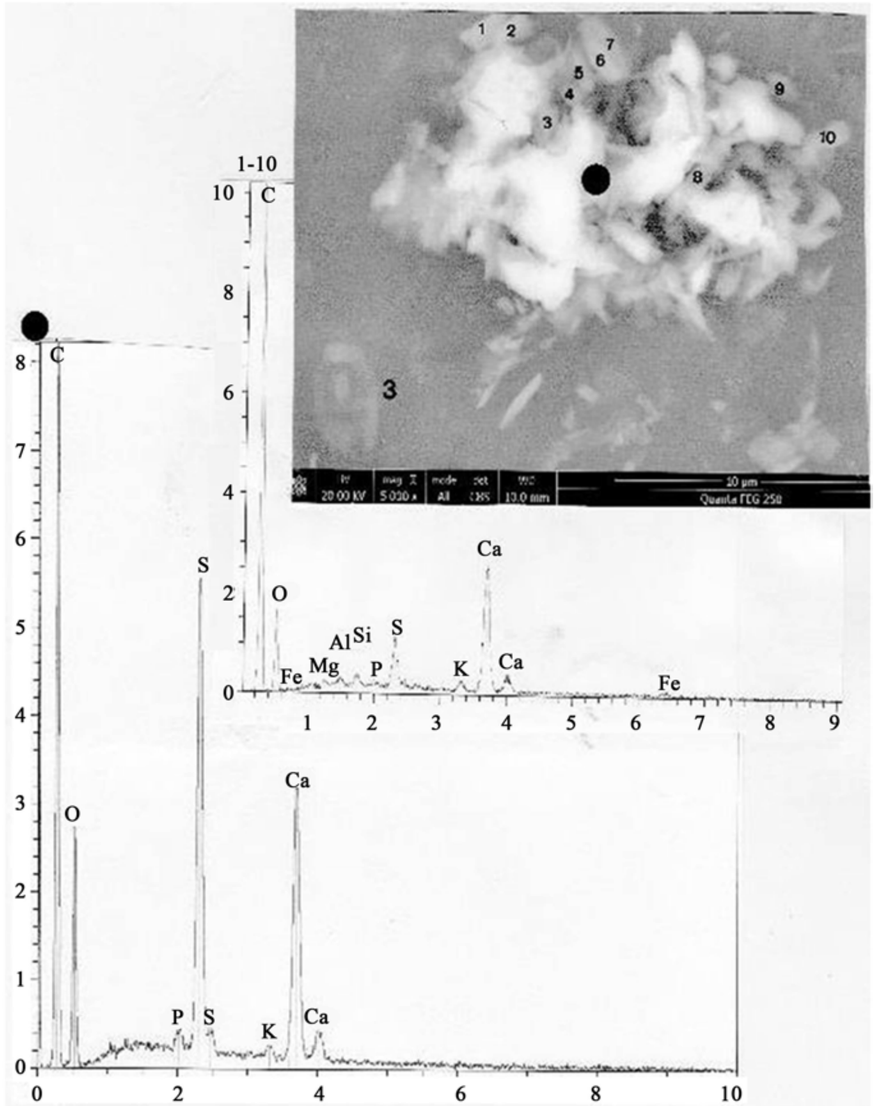


Figure 4. Gypsum and aragonite crystals on hair number **3**. *Above*: SEM photograph (in CBS, 5000×) of the pile of gypsum crystals located on another part of a hair number 3 portion (1 - 10: little mineral particles). *Below*: spectrum at the black dot; upper spectrum: 1 - 10 spectras.

(Figure 6); its spectrum is more complex than that of the first salt particle, including notably some part of potassium chloride (KCl) in its spectrum. By this way it looks like a conglomerate of marine salt.

Supplementary Figure 1 gives the aspect and composition of a commercial powder of marine salt, used here as the marine salt powder of reference. Examination of this powder shows that it is constituted of sodium chloride, potassium chloride and magnesium chloride particles.

3.3. Microorganisms

3.3.1. Diatoms

Diatoms are monocellular algae shut away in a theque (the frustule) of silica

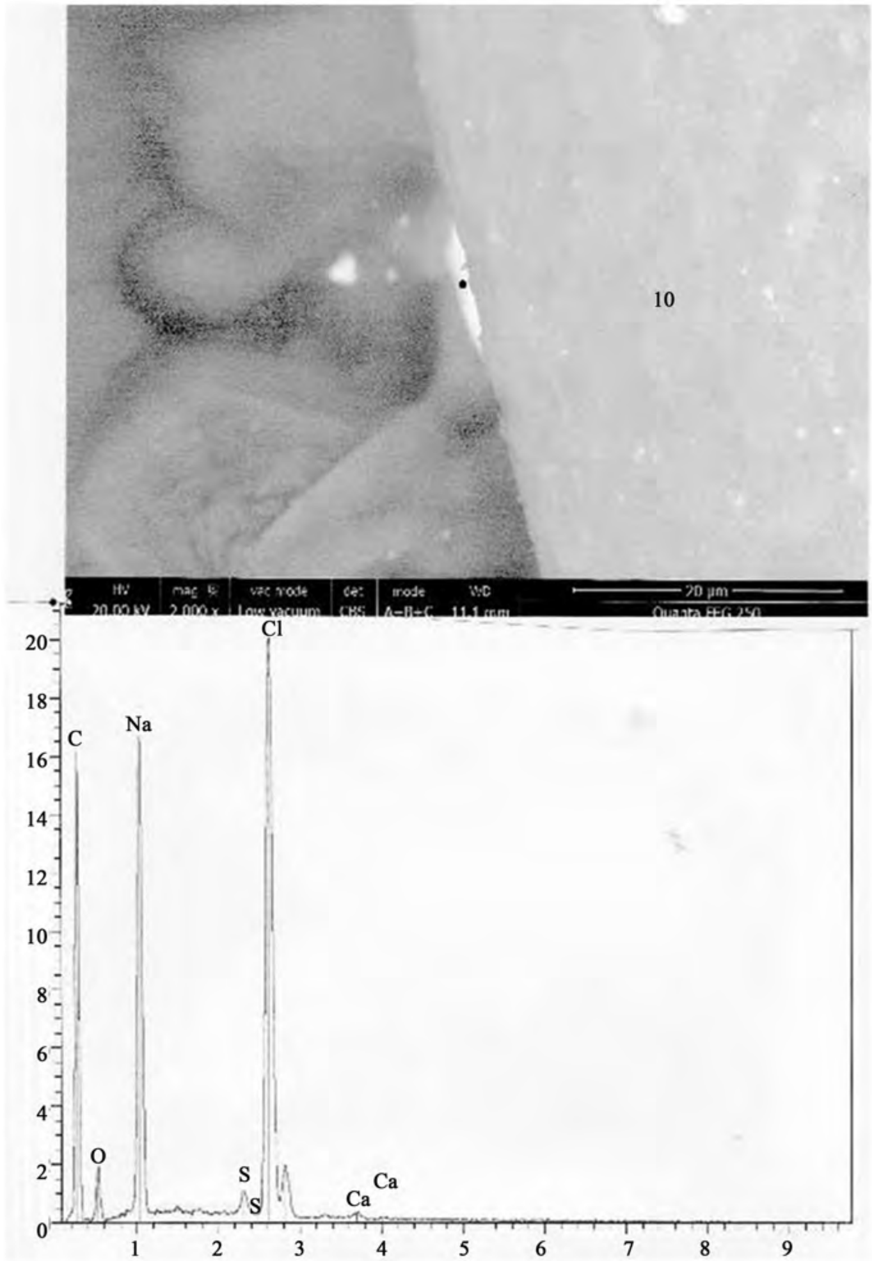


Figure 5. A salt powder on the hair number **10**. *Above*: SEM photograph (in CBS, 2000×) showing the powder. *Below*: spectrum at the little black dot. C: carbon; O: oxygen; Na: sodium; S: sulphur; Cl (two peaks): chlorine; Ca: calcium.

(Steckbach & Kocialek, 2011). The first complete diatom observed is that represented in photographs of **Figure 7**: it is a circular diatom (located at the vicinity of hair number 2), of a mean diameter of about 15 µm and with many pores at the periphery of the frustule. Its elemental composition is silicium-rich.

Figure 8 shows an incomplete diatom frustule (broken at the right side), located on hair number 1. Diameters of the pores are of about 213 nm.

The diatom of the photograph of **Figure 1** is seen in an enlarged view (4000×) on photograph of **Figure 9**. Its form is also circular, but with a smaller diameter

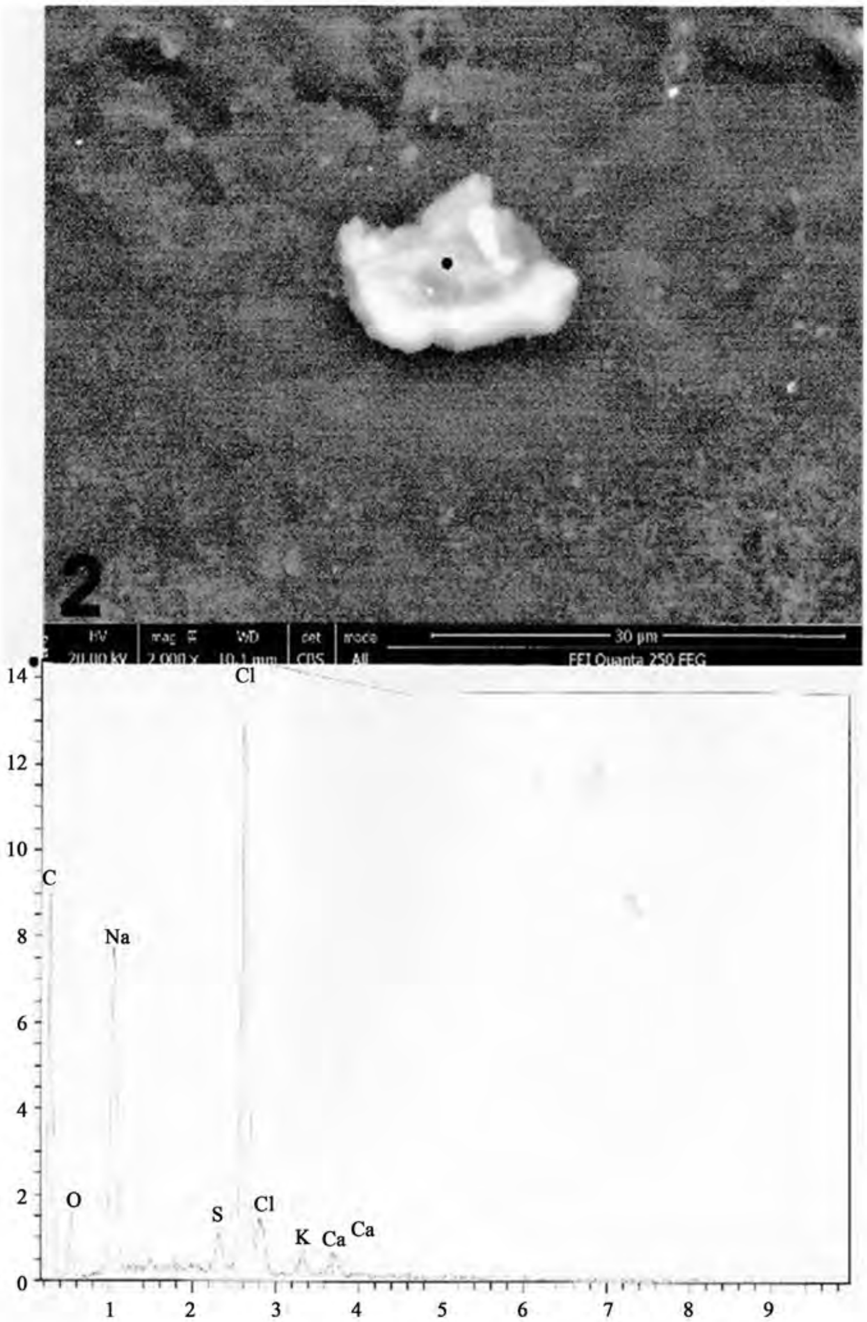


Figure 6. Another salt particle on the hair number **2**. *Above*: SEM photograph (in CBS, 2000×) showing the particle. *Below*: spectrum at the little black dot. C: carbon; O: oxygen; Na: sodium; S: sulphur; Cl (two peaks): chlorine; K: potassium; Ca (two peaks): calcium.

(about 8.5 µm); pores are also located at the frustule periphery, but are elongated among the diameter and of greater sizes.

Other diatoms are observed on other hairs. But the outlines of their frustules are not clearly visible (Figure 10 shows the example of a diatom located on hair number 9), because coated with the organic material (only the pores can be distinguished).

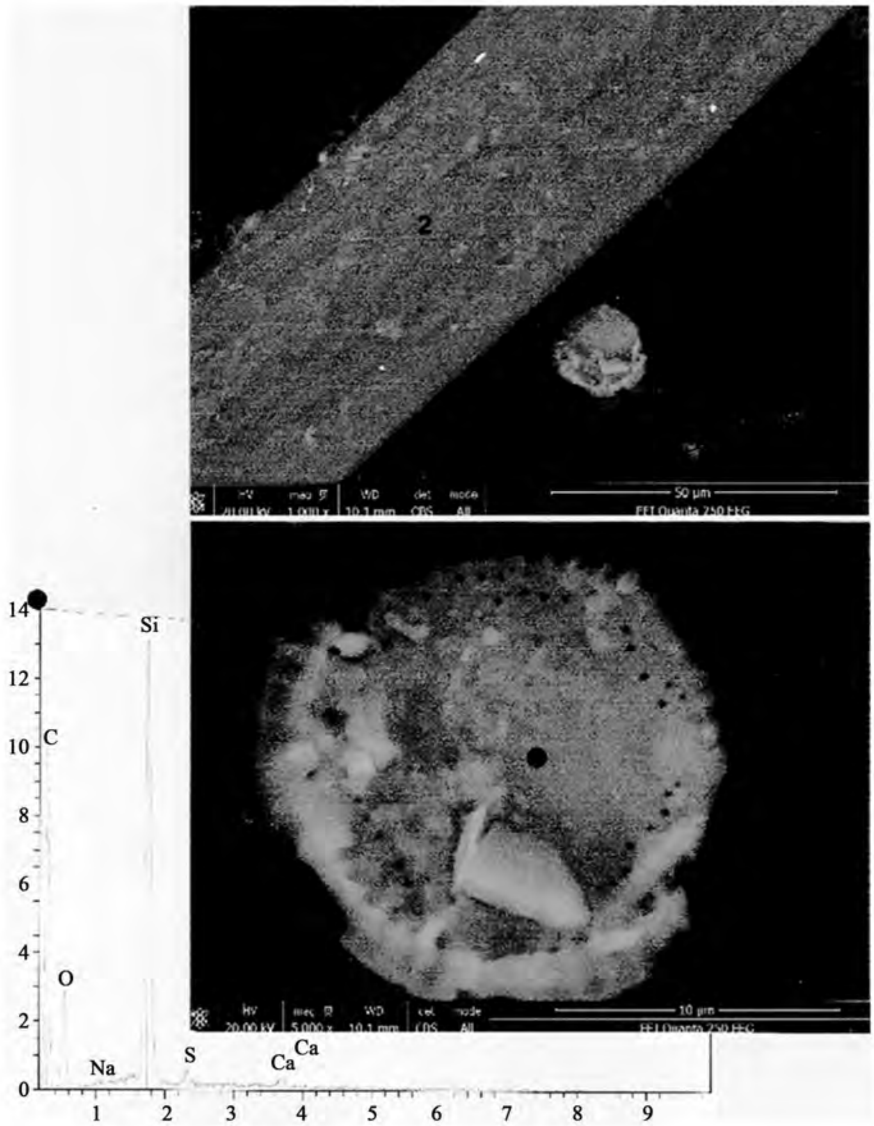


Figure 7. The first complete diatom observed, at the proximity of hair number **2**. *Upper photograph*: SEM photograph (in CBS, 1000×) showing the diatom at the proximity of an hair **2** portion. *Lower photograph*: enlarged photograph (5000×) of the diatom. *Below*: spectrum at the black dot. C: carbon; O: oxygen; Na (traces): sodium; Si: silicium; S: sulphur; Ca: calcium.

Diatoms observed are of the Centric category. They are probably (Ludes & Coste, 1996) of the species *Thalassiosiraweissfloggii* for the specimen shown on **Figure 7**, and of the species *Paraliasulcata* for that shown on **Figure 9**; both are marine species. In their determination (Charlier et al., 2017) suggest that the only species of diatoms they observed on the hair surfaces of Marie-Madeleine is *Cyclotellameneghiniana.*

3.3.2. Coccoliths

Coccolith are marine monocellular algae, characterized by their shield (the coccosphere, constituted of multiple micro-plaques) of calcium carbonate. In fact,

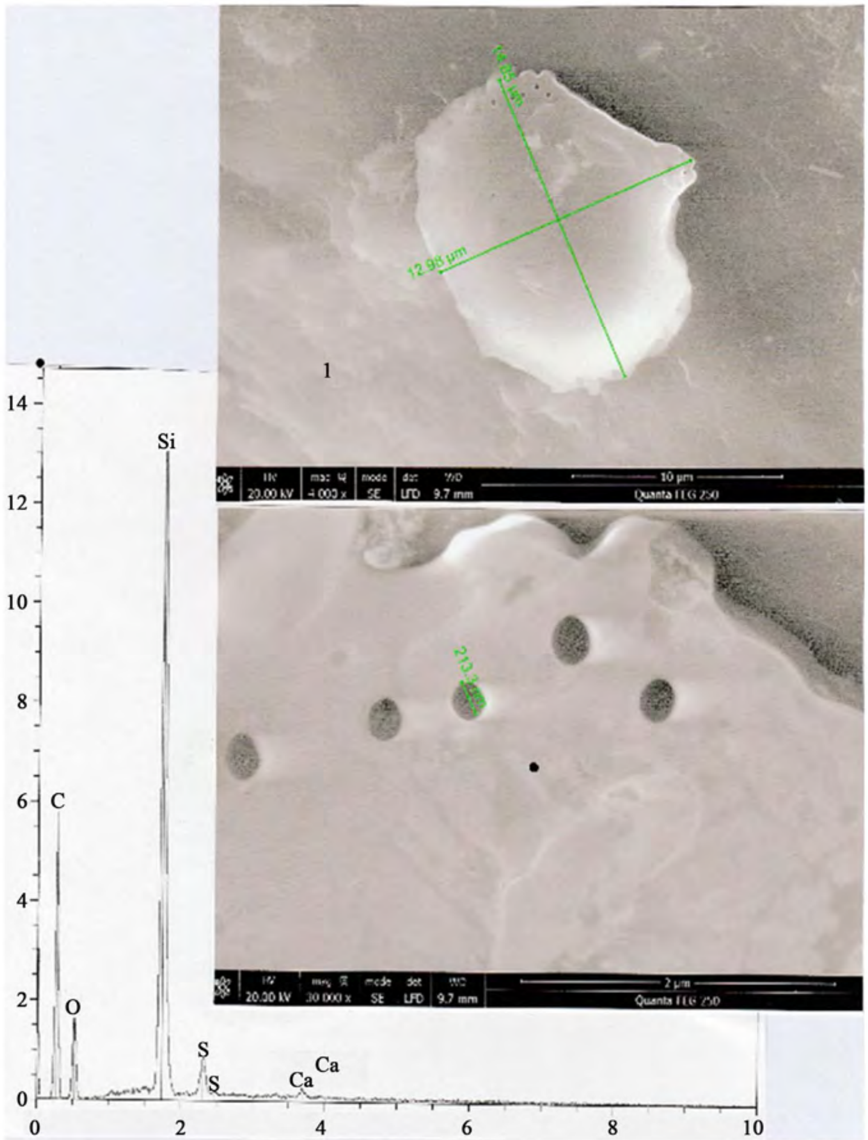


Figure 8. The second diatom observed, on hair number **1**. *Upper photograph*: SEM photograph (in LFD, 4000×) showing this broken diatom on hair **1** potion. *Lower photograph:* enlarged photograph (30,000×) showing the diatom pores. *Below:* spectrum at the little black dot.

the photograph of Figure 10 shows two of them (numbered 1 and 2) near the diatom; they are of oblong forms (measuring 5.8 µm of maximal length) and of calcium carbonate composition.

The photographs of Figure 11 show detailed views (both in LFD and in CBS) of an example of one coccolith located near some portion of hair number 10. The form is ovoid, and with a maximal length of about 8.5 µm. This sample is given here because it has a typical (non-altered) form, shape and aspect; micro-plaques constituting the coccosphere are clearly visible (they are jointive, and of approximate dimensions of about 1 - 2 µm each). The corresponding spectrum is highly calcium-rich.

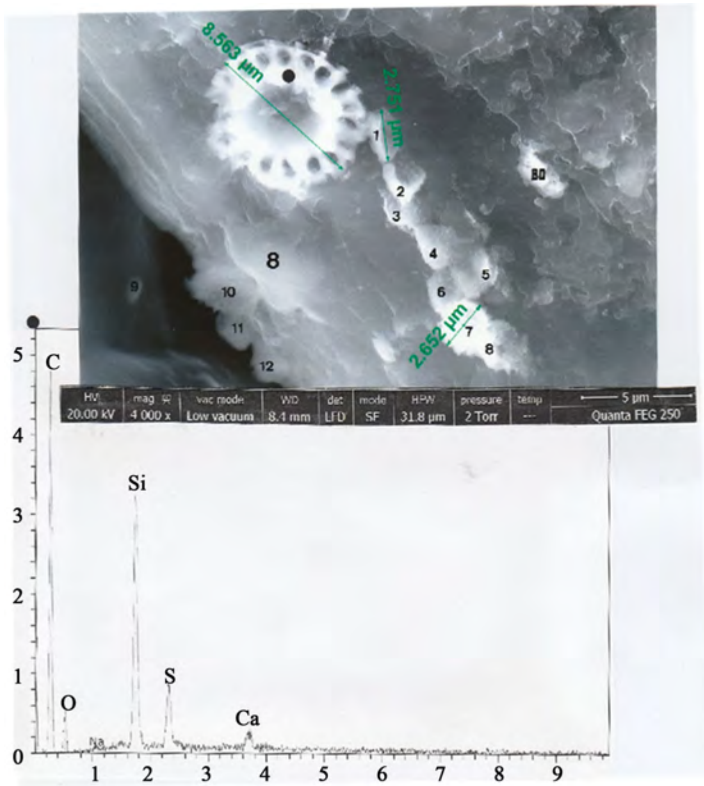


Figure 9. Two diatoms on an hair number **8** portion. *Above*: SEM photograph (in LFD) showing an enlarged (4000×) view of the rectangle area of Figure 1. BD: broken part of another diatom; 1 - 12: modern spores. *Below*: spectrum at the black dot.

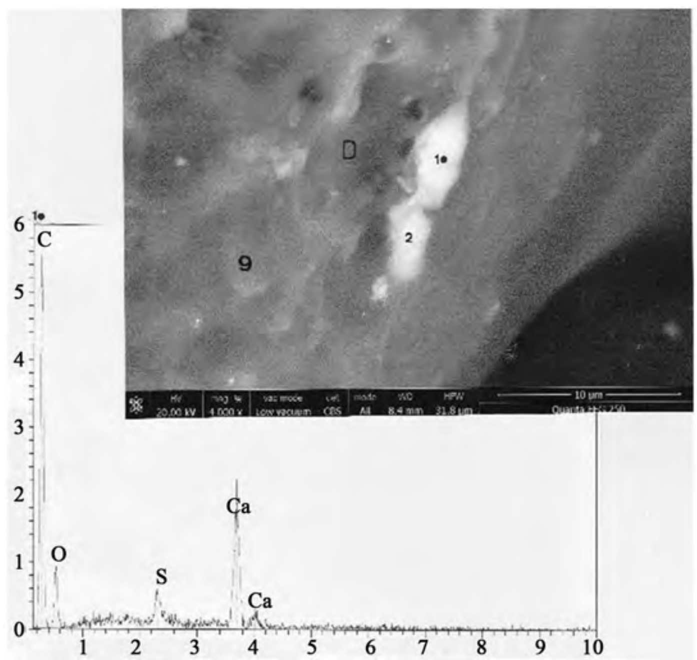


Figure 10. Another diatom (observed by pores only) on hair number **9**. *Above*: SEM photograph (in CBS, 4000×) of the diatom (D), located at some part of hair number **9** (1 and 2 are two adjacent particles located near the diatom). *Below*: spectrum (in 1) at the little black dot. C: carbon; O: oxygen; S: sulphur; Ca (two peaks): calcium.

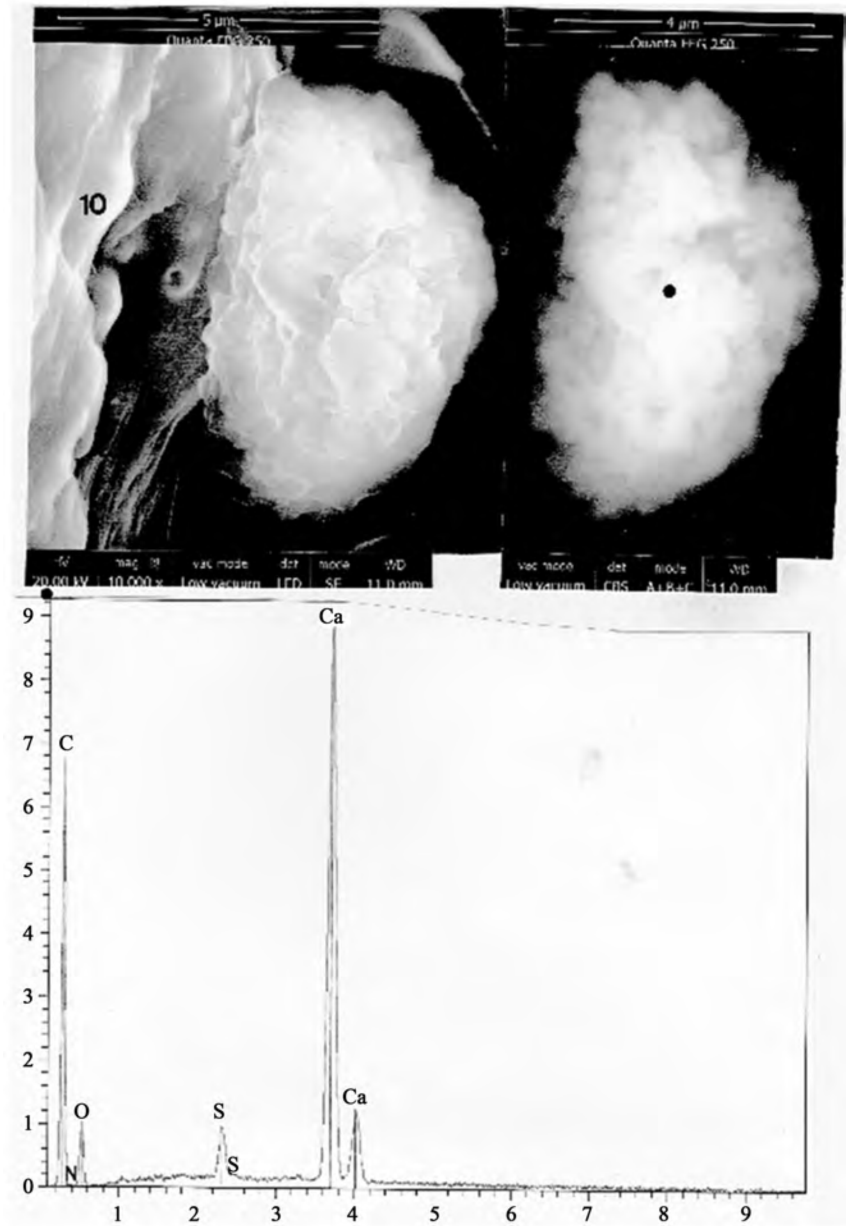


Figure 11. One coccolith located near the hair number **10**. *Above*: SEM photographs (in LFD at the left, and in CBS at the right) 10,000× of the coccolith, located at the proximity of a portion of the hair number **10**. *Below*: spectrum at the little black dot. C: carbon; N (traces): nitrogen; O: oxygen; S (two peaks): sulphur; Ca (two peaks): calcium.

Figure 12 gives a first example of a coccolith located on hair number 2, and Figure 13 shows another coccolith located in another portion of this hair. Generally, Coccoliths are not present in a separate form at the surface of the hair; Figure 14 gives an example of at least five coccoliths, grouped together, on a third portion of the hair number 2.

We found coccolith samples in almost all of the ten hairs studied; but, for unknown reasons, hair number 2 contains the greatest number (up to 46 samples were accounted on its) of coccoliths observed.

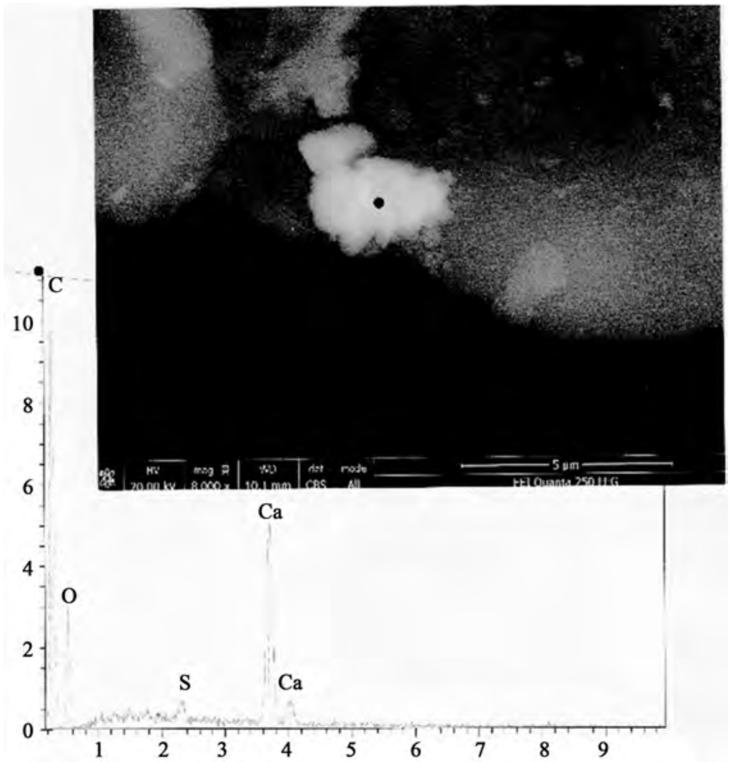


Figure 12. *Above*: SEM photograph (in CBS, 8000×) of another coccolith, located on a portion of hair number **2**. *Below*: spectrum at the little black dot.

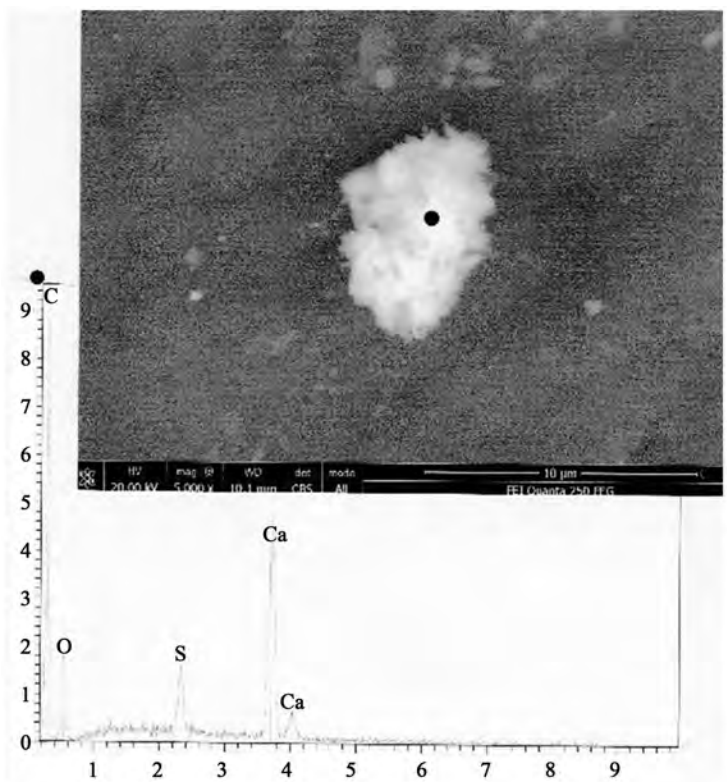


Figure 13. *Above*: SEM photograph (in CBS, 5000×) of a second coccolith located on another portion of hair number **2**. *Below*: spectrum at the black dot.

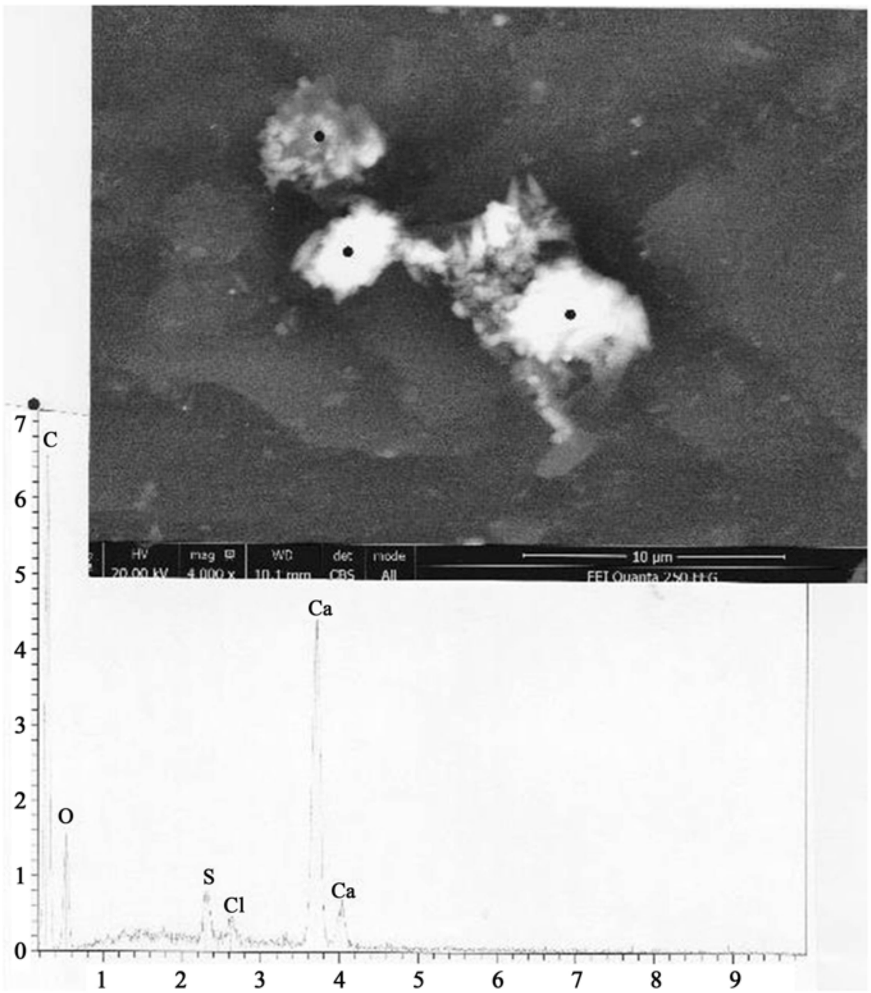


Figure 14. *Above*: SEM photograph (in CBS, 4000×) of a group of six coccoliths located on another portion of hair number **2**. *Below*: common spectrum (at little black dots) of three of them.

All the coccolith specimens observed here belong to the same species (Heimdal, 1993). According to shape, dimensions and peculiarities in micro-plaque morphology, this species is probably *Sphaerocalyptraquadridentata* (commonly found in the Mediterranean Sea).

3.3.3. Tintinnids

Tintinnids are all members of the suborder Tintinia; they are planktonic Ciliates, a group of microorganisms playing an important role in marine pelagic food webs. Characterized by the possession of a lorica, tintinnids have been catalogued in various plankton collections (Corliss, 1979).

The first specimen of tintinnid observed is shown on **Figure 15**. It is located near some part of hair number 4. Outlines of its cytoplasm can be observed in LFD: the lorica is of triangular form (of about 25 µm of maximal height), with a marked superior point (visible at the left corner of the photograph) indicating the stem of the lorica, and an irregular inferior border (visible on the right of the

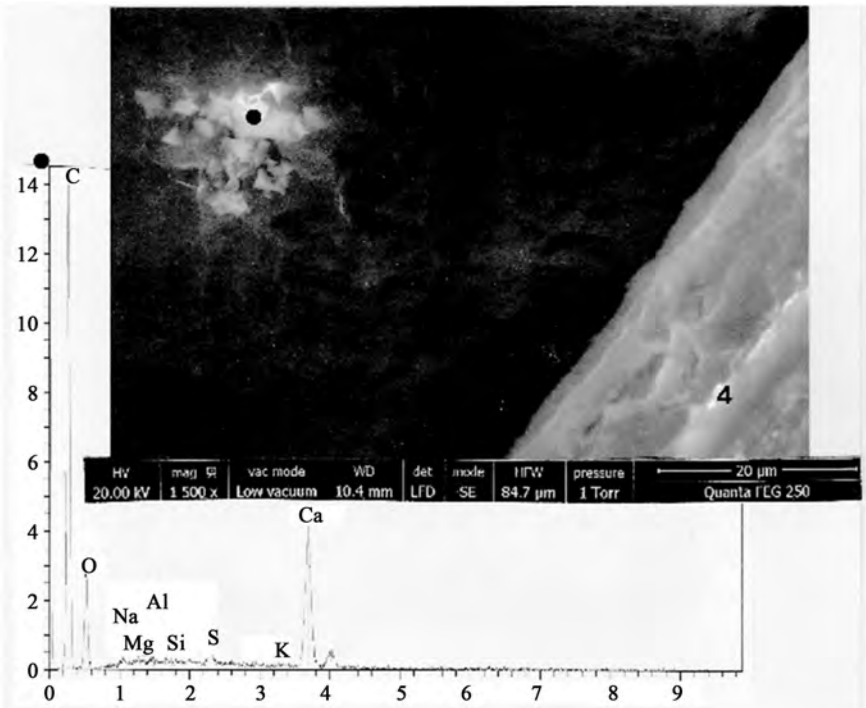


Figure 15. A tintinnid located near the hair number **4**. *Above*: SEM photograph (in LFD, 1500×) of the tintinnid specimen, near a portion of hair number **4**. *Below*: spectrum at the black dot. C: carbon; O: oxygen; Na: sodium; Mg: magnesium; Al (traces): aluminium; Si (traces): silicium; S: sulphur; K (traces): potassium; Ca (two peaks): calcium.

photograph). The lorica ornamentation is made up of small micro-plaques (of calcium carbonate) of triangular forms.

A second tintinnid specimen, located near hair number 9, is shown on the photograph of **Figure 16**, Somehow deformed, we can distinguish the superior point of the triangular form of the lorica (at the right corner of the photograph). As for the previous specimen, lorica ornamentation is made up of small micro-plaques (of triangular, but with more acute forms) of calcium carbonate. A third tintinnid specimen, located on hair number 10, is shown on the photograph of **Figure 17**. Of more little size (of about 6 µm of maximal length), it emerges from a corresponding micro-cavity of the hair. The superior point of the lorica is well visible at the bottom of the photograph.

The more characteristic tintinnoid specimen is that shown on the photograph of **Figure 18**; it is braced to anotherpart of hair number 10. Its triangular outlines are clearly shown on the photograph, the superior point of the triangle being at the left inferior part. Lorica ornamentation is made of very little micro-plaques, also of triangular forms. The highly resolutive spectrum of the cytoplasm shows that it is mainly constituted of organic material (carbon and oxygen) plus some sulphur component.

All the five specimens observed belong to the same species (based on the form and dimensions of the lorica):*Rhabdonella spiralis*, which is a relatively commonly observed Tintinoid in the Gulf of Marseilles (Travers & Travers, 1971).

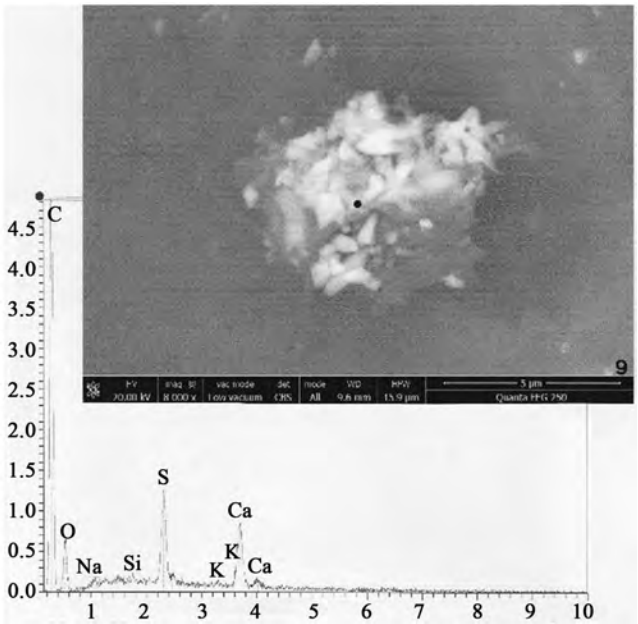


Figure 16. Another tintinnid located near the hair number **9**. *Above*: SEM photograph (in CBS, 8000×) of the tintinnid specimen, near a portion of hair number **9**. *Below*: spectrum at the little black point. C: carbon; Na: sodium; Si: silicium; S (two peaks): sulphur; K (traces): potassium; Ca (two peaks): calcium.

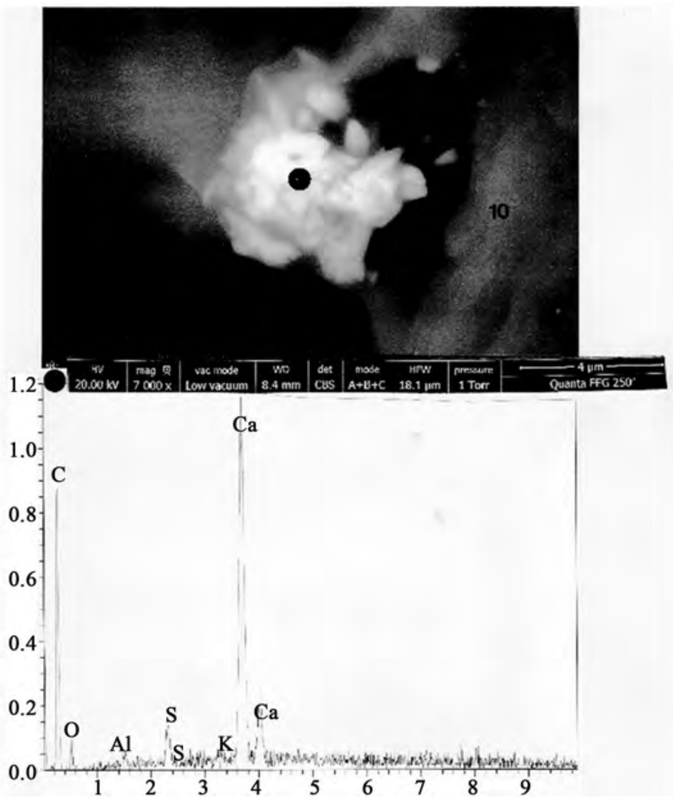


Figure 17. A third tintinnid located on the hair number **10**. *Above*: SEM photograph (in CBS, 7000×) of the tintinnid specimen, on a portion of hair number 10. *Below*: specimen at the black dot. C: carbon; O: oxygen; Al: aluminium; S (two peaks): sulphur; K (traces): potassium; Ca (two peaks): calcium.

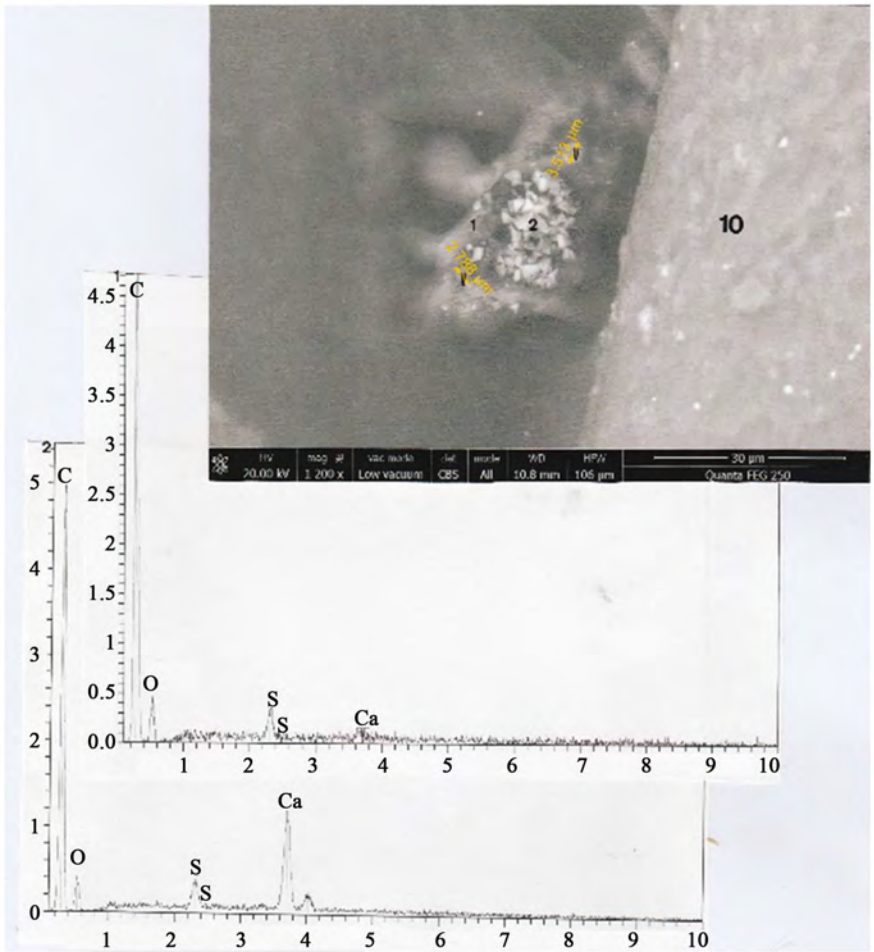


Figure 18. A fourth tintinnid located on hair number **10**. *Above*: SEM photograph (in CBS, 1200×) of the tintinnid specimen, on another portion of hair number **10**. (1: the left border of the cytoplasm of the specimen; 2: the center of the specimen, constituted mainly of triangular micro-plaques; arrow points indicate two quasi-spherical micro-particles. *Below*: lower spectrum (of 2); upper highly resolutive spectrum (of 1). C: carbon; O: oxygen; S (two peaks): sulphur; Ca (two peaks): calcium.

3.4. Algae Fragments

Photography of Figure 19 shows another thalle' fragment of an algae, which surround some part of hair number 10. Such a formation is characteristic of algae, because the fine nervation observed along the thalle surface is oriented longitudinally among the thalle axis. Spectrum of the thalle is mainly constituted of organic matter, where the potassium (an element characteristic of vegetables in general) is at equal value to that of calcium. It corresponds to a marine algae, because of the relative contents of chlorine and sodium (ClNa).

The upper photograph of Figure 20 shows a more consequent (of 500 µm of greater dimension) fragment of the thalle of a third specimen of an algae, located near hair number 5. Enlargement (1200×) of its right extremity shows that it is constituted of flat and wawythalle filaments, some of them presenting the characteristic fine and longitudinally oriented nervation. The spectrum of one

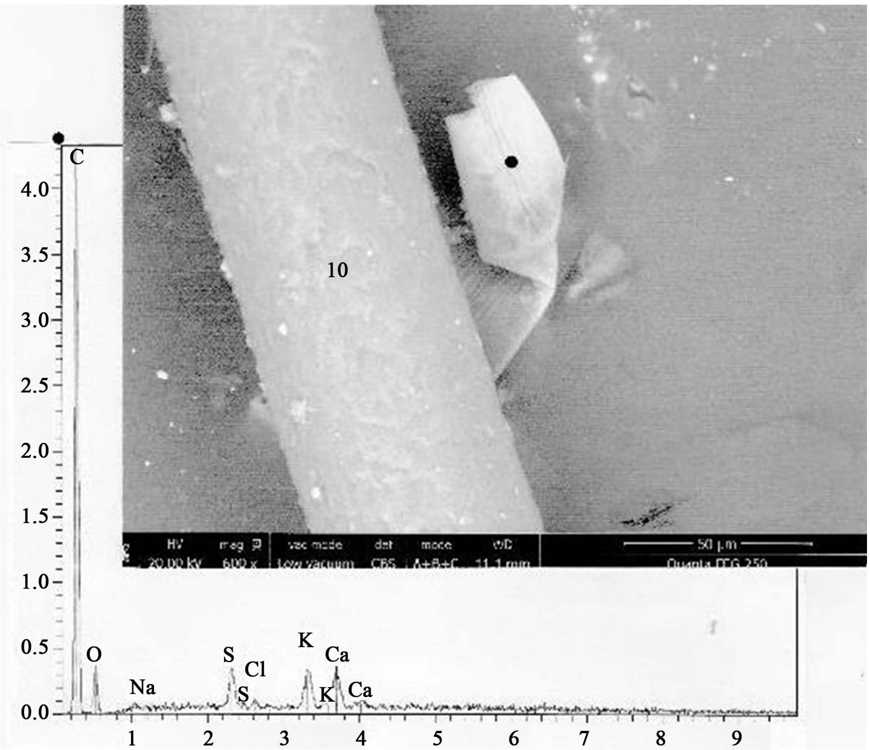


Figure 19. Another algae fragment on hair number **10**. *Above*: SEM photograph (in CBS, 600×) of a thalle portion of the algae, surrounding some part of hair number **10**. *Below*: spectrum at the little black dot. C: carbon; O: oxygen; Na: sodium; S (two peaks: sulphur); Cl: chlorine; K (two peaks): potassium; ca (two peaks): calcium.

portion of them shows the same characteristics to those of the previous specimen: importance of the organic matter, relatively high content of potassium relatively to calcium, presence of ClNa; we can conclude that this specimen is also one of some marine thalle algae.

Supplementary Figure 2 gives the aspect and composition of a thalle fragment of *Fucus* of reference. Micro-structural aspect of the thalle and its spectrum are similar to those of the third thalle fragment studied. We deduced that this thalle fragment is of the fucussort.

3.5. Parts of Micro-Crustaceans

Crustaceans form a large arthropod taxon. Like other arthropods, crustaceans have an exoskeleton that contains chitine (the addition of calcium carbonate makes them harder). They are distinguished from other groups of arthropods by the possession of biramous appendages (a biramous limb branches into two series of segments attached end-to-end). Most crustaceans are marine animals.

Some observations suggest that there are some debris of micro-crustaceans on the surface of some hairs. For example, photograph of Figure 21 shows a relatively voluminous quasi-rectangular (of about 27 µm of length on 7 µm of width) shell portion (with an appendage), located on some part of hair number 8. Spectras at both extremities of the fragment show show some crustacean characteristics:

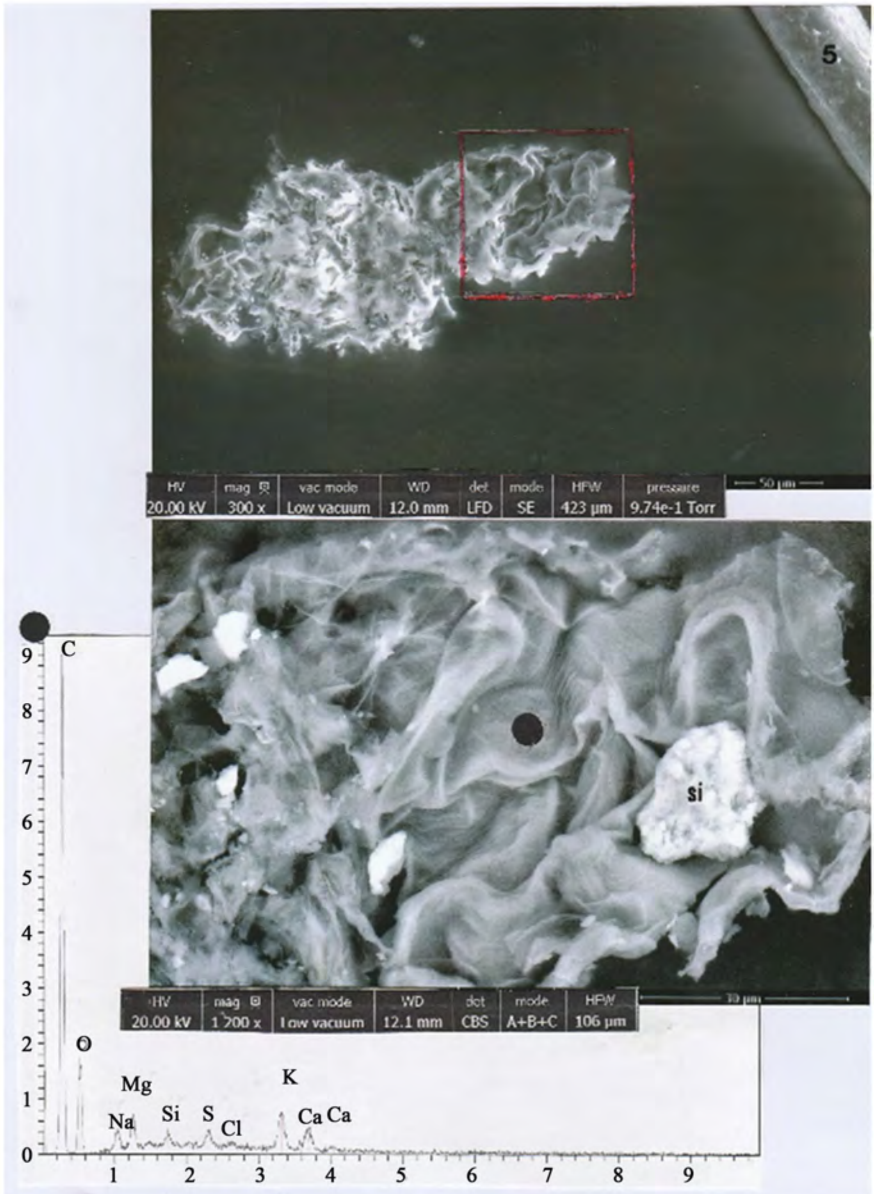


Figure 20. A third thalle of an algae located in the vicinity of hair number **5**; *upperphotograph*: (in LFD, 300×) of the thalle; the red rectangle area is enlarged in the below photograph. *Lower photograph*: SEM photograph (in CBS) of the enlarged (1200×) rectangle area; Si: a silica particle. *Below*: spectrum at the black dot. C: carbon; O: oxygen; Na: sodium; Mg: magnesium; Si: silicium; Cl: chlorine; K: potassium; Ca (two peaks): calcium.

it is mainly constituted of organic matter, that of the chitine $(C_8H_{13}NO_5)n$; it contains appreciable amount of calcium carbonate, but also some part of calcium phosphate; it has a high content of sulphur (these two last distinctive features being highly crustacean specifics of their exoskeleton).

Photographs of Figure 22 show several samples of binamous appendage portions, located on hair number 4 and 5. The spectrum of that located on hair number 4 surface contains chitine mainly, with an elevated level of calcium carbonate, a relatively amount of sulphur, and some part of calcium phosphate. The

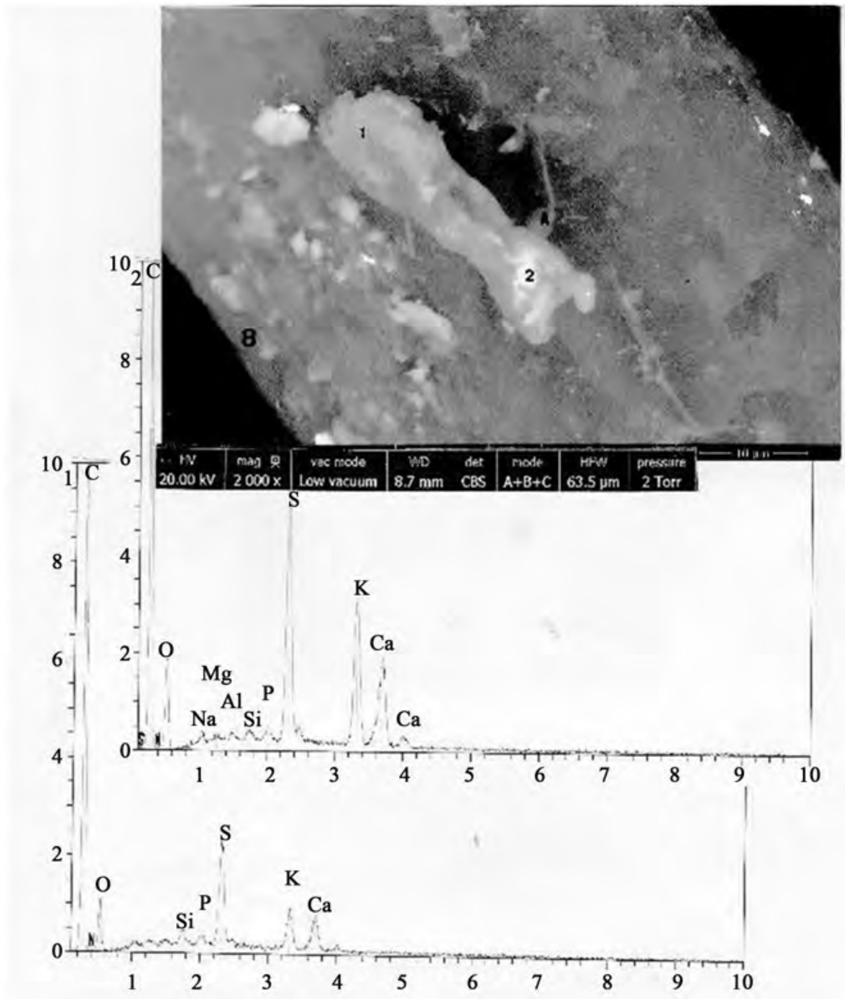


Figure 21. A shell portion of a crustacean on hair number **8**. *Above*: SEM photograph (in CBS, 2000×) of the shell portion, located on some part of hair number **8** (1: the smooth portion of the shell; 2: the granulous portion of the shell; A: an appendage). *Below*: lower spectrum: that of 1. Upper spectrum: that of 2. S (three peaks): sulphur; C: carbon; N: nitrogen; O: oxygen; Na: sodium; Mg: magnesium; Al: aluminium; Si: silicium; P: phosphorous; K: potassium; Ca (two peaks): calcium.

surface and extremity of this biramous appendage is locally covered by salt crystals (of cubic forms), that establishing the marine nature of the sample.

Entire fragments of crustacean shield bodies, some with appendages, were preserved on some hair surfaces. Two examples of such specimens are given in Figure 23, one near hair number 4 and the other on hair number 9 surface; both specimens show sheet rows of jointive plaques (Table 1), laterally dorsally or ventrally oriented in comparison to the longitudinal axis of the body of the mirco-crustacean samples. In both cases, spectras of the two fragment surgaces are compatible to that of a marine micro-crustacean debris.

Supplementary Figure 3 shows lateral dorsal and ventral pieces of the shell of a cooked pawn. Spectras of the surfaces of these two pieces are representative of the spectrum of reference of the shell skeleton of a marine micro-crustacean.

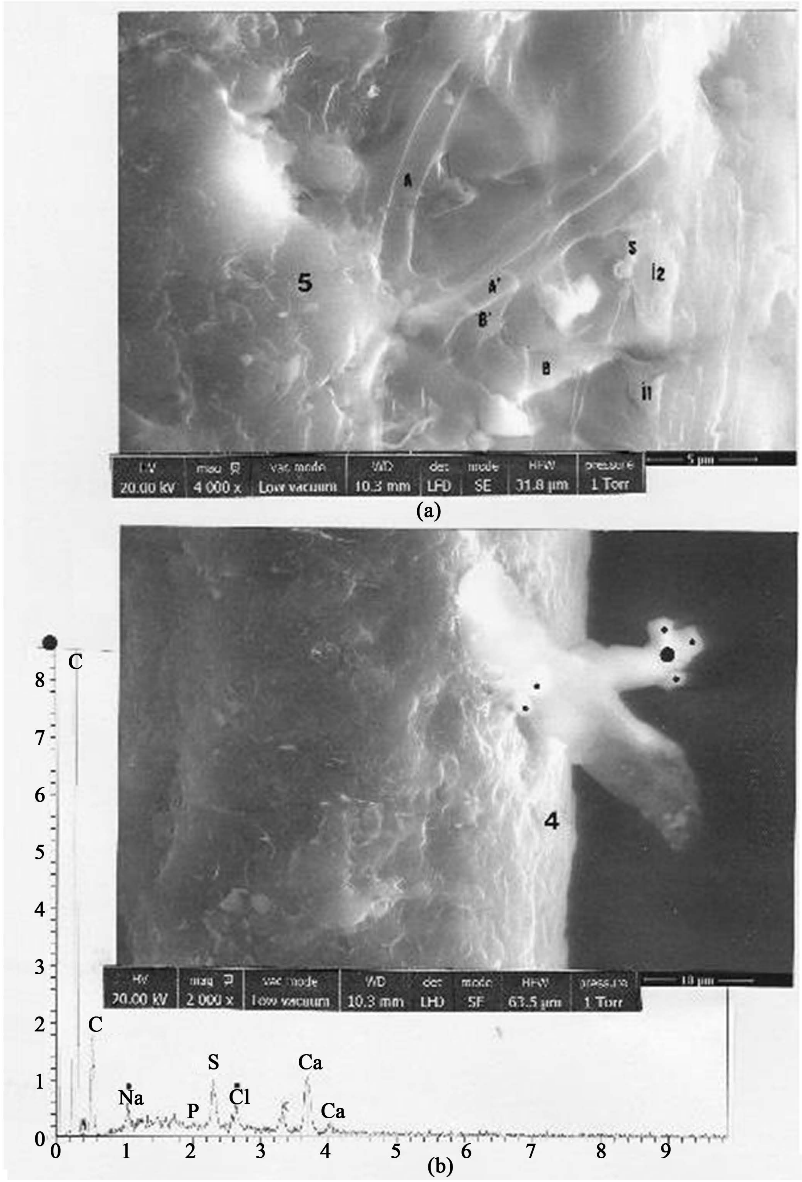
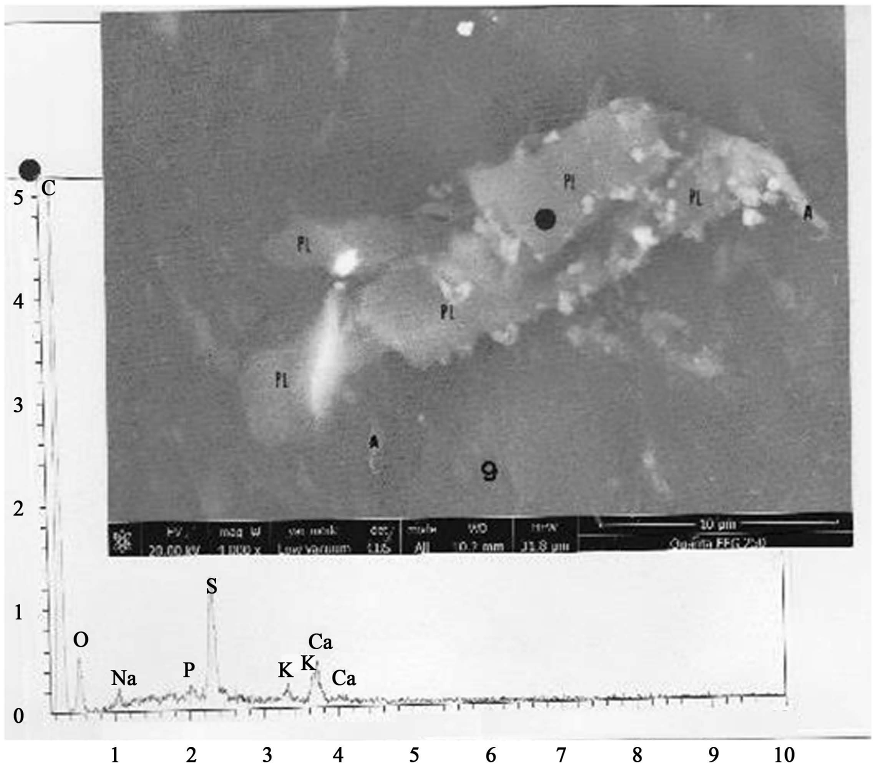


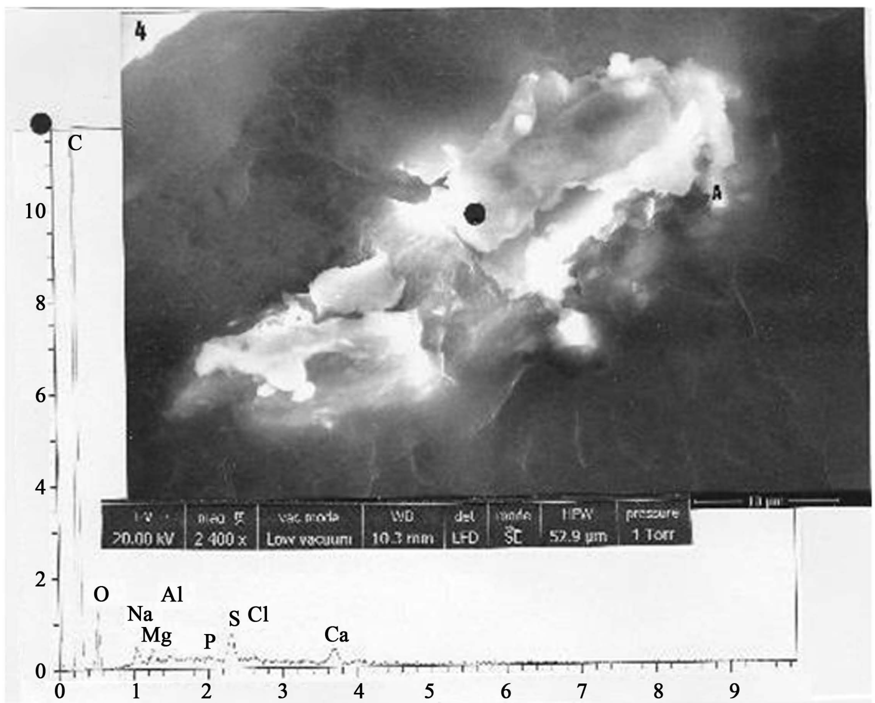
Figure 22. Crustacean appendages on hair number **4** and **5**. *Upper (A) photograph*: SEM photograph (in LFD, 4000×) of some portions of binamous appendages located on some part of hair number 5. AA' and BB': the two parts of two biramous appendages A and B; i1 and i2: some portions of appendages; S: bristle of an appendage. *Lower (B) photograph*: SEM photograph (in LFD, 2000×) of a biramous appendage portion located at the right border of some part of hair number **4**; little points indicate particle of salt crystals. *Below*: spectrum at the black dot. C: carbon; N: nitrogen; O: oxygen; Na: sodium; P (traces): phosphorous; S: sulphur; Cl: chlorine; K: potassium; Ca (two peaks): calcium. Na and Cl elements are pointed.

Table 1. Characterization of the two crustacean shell sheets observed.

	Total lengths of the samples	Numbers of dorsal plaques	Number of ventral plaques
That on hair number 9	25 µm	4	1
That near hair number 4	45 µm	6	3



(a)



(b)

Figure 23. Crustacean shell sheets on hair number **9** and at the vicinity of hair number **4**. **A**: shell sheets on some part of hair number **9**. *Above*: SEM photograph (in CBS, 4 000×) of the shell sheats. PL: the sheets; A: appendages. *Below*: spectrum at the black dot. **B**: shell sheets at the vicinity oh hair number **4** (A: appendage). *Above*: SEM photograph (in LFD, 2400×) of the shell sheets. *Below*: spectrum at the black dot.

4. Discussion

Exploration of the surfaces of ten Marie-Madeleine's hairs permits us to detect numerous micro-remains of marine origin. These remains (Table 2) are minerals, diatoms, coccoliths, tintinnides, and micro-fragments of algaes and crustaceans.

Table 2. Marine micro-remains found oh hairs.

Sorts of micro-remains	Those illustrated	Corresponding photographs of figures
Gypsum (deposits on almost all of the hairs)	One deposit on hair 1	Figure 2
	One deposit on hair 3	Figure 3
	Another deposit (crystals in "fer de lance") on hair 3	Figure 4
	One deposit on hair 8	Figure 1
Aragonite	Ten characteristic crystals on hair 3	Figure 5
Salt (two specimens observed)	A salt deposit on hair 10	Figure 5
	A marine salt deposit on hair 2	Figure 6
Diatoms (four specimens observed)	One on hair 1	Figure 8
	One on hair 2	Figure 7
	One on hair 8	Figure 9
	One on hair 9	Figure 10
Coccoliths (located on almost all of the hairs)	One on hair 2	Figure 12
	Another on hair 2	Figure 13
	Five others on hair 2	Figure 14
	Two on hair 9	Figure 10
	One on hair 10	Figure 11
Tintinnids (four specimens observed)	One near hair 4	Figure 15
	One near hair 9	Figure 16
	One on hair 10	Figure 17
	Another on hair 10	Figure 18
Thalle fragments of an algae	Two fragments on hair 8	Figure 1
	One fragment on hair 10	Figure 19
	A relative big portion near hair 5	Figure 20
Fragment of a crustacean shell	On hair 8	Figure 21
Fragments of crustacean appendages	On hairs 4 and 5	Figure 22
Fragment of crustacean shells	Shell sheets on hairs 4 and 9	Figure 23

That establishes that the hairs of the corresponding person were soaked with some sort of marine environment, that of the sea water. According to the "tradition des Saints de Provence" (Franzoni, 2015) Marie-Madeleine, at the last period of her life, retired for thirty years in a cave of the Mountains of the Sainte-Baume.

That we know is the present composition of this cave ceiling (**Supplementary Figure 4**). Mineral particles of the corresponding coating are rich in carbon, aluminium and calcium; it represents (Winter, 2012) a sort of cement of calcium aluminate, obtained by fusion of a mixture of limestone ($CaCO_3$) and bauxite (Al_2O_3), the main component of this cement being monocalcic aluminate ($CaO \cdot Al_2O_3$). This sort of cement was find during the 19th Century, to replace the Portland cement in the stucrural concretes exposed to sulphatic attacks. This coating was used at that times on the walls and the ceiling of the cave to prevent the numerous taking of pilgrims (who used it as a relics).

Such a coating masks the original matter of the walls of the cave. We found no particles of this sort of coating in a systematically exploration of all of the hair surfaces (that establishes that hairs studied were taken from the cave before the period of this coating invention). The only particle of cement we found on hair surfaces is that represented on **Figure 24**; it is a small (of about 10µm of diameter) rounded particle, brighting to electrons, located on a surface portion of hair number 10. Its spectrum shows that it is another form of cement (Winter, 2012), constituted mainly of an artificial aluminosilicate that is iron-rich. This particle is certainly an artefact, deposited on the surface of the hair during the recent period.

Abundance and diversity of marine micro-remains deposited on hairs suggest that they were submerged in sea water. An explaining hypothesis of the presence of these micro-remains on hairs is to admit that Marie-Madeleine was transported by her companions as a dead body (like a mummy) during the marine transport from Palestine to Provence coasts. There are some bibliographic evidence that, during the Antiquity, ancient Jews travelled with the bodies of their dead relatives (Grossi, 2012).

Such a transport is documented (**Figure 25**) in an ornamentation part of the reliquary of the Sainte-Baume, containing a presumed osseous of Marie-Madeleine. We can clearly distinguish on this illustration, lying down at the terminal part of a small boat, the corpse and the face profile of a mummy (with strips); the corresponding person represented must be of some importance, because he had a limb.

In this hypothesis, it was a cadaver that had been exposed at the top of the Sainte-Baume mountain and the "tradition des Saints de Provence" is legendary.

The photograph of **Supplementary Figure 5** shows at increased magnification (3000×) mineral particles of the cement coating the ceiling sample: underlying smaller particles are seen between the cement particles; more than their small sizes (less than 5 µm of maximal length), they can be recognized by their

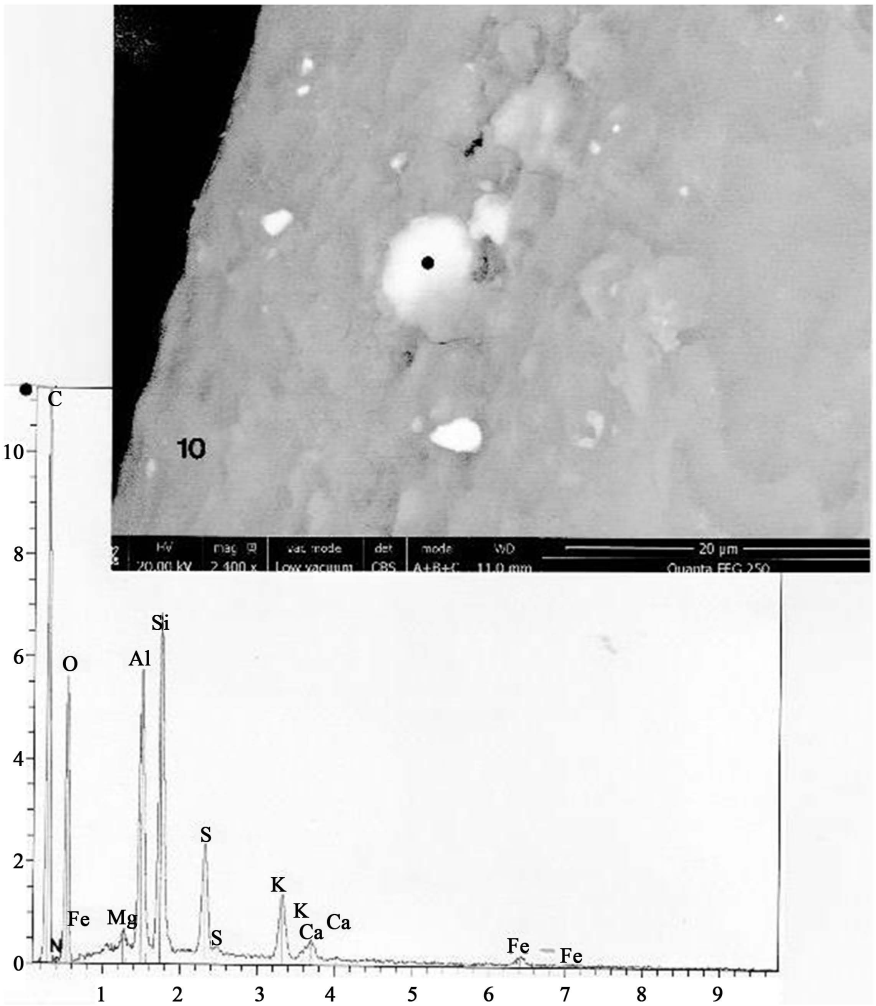


Figure 24. Study of a cement particle on hair number **10**. *Above*: SEM photograph (in CBS, 2400×) showing a rounded particle (black dot) on a portion of hair number 10 surface. *Below*: spectrum at the black dot. C: carbon; N (traces): nitrogen; Fe (three peaks): iron; Mg: magnesium; Al: aluminium; Si: silicium; S (two peaks): sulphur; K (two peaks): potassium; Ca (two peaks): calcium.

Figure 25. One of the ornamentations located at the basis of the reliquary of the Sainte-Baume (realized in 1899 by Thomas Caillat, at the request of the Terris family), where the mummy (arrow points) is represented (source: Tibot M. A. & Douzet A. (2011). Marie-Madeleine; sur les chemins secrets de France. Tournai: Fortuna).

creneled outlines, and by their differential aspect (they are darker than those of cement) in CBS.

Their corresponding spectras are characterized by two main peak values of sulphur and barium (so it corresponds to some form of barium sulphate), but with an appreciable amount of strontium. This composition corresponds in fact to that of barytine ($BaSO_4$, with strontium traces), a typical mineral particle of hydrothermal origin.

If the corpse (the dead body) was located under the ceiling of the cave for a long time, we must find on her hair some particles of barytine dating from the pre-coating procedure. Well it is effectively the case: photograph of Figure 26 shows a first example of one barytine particle deposited on some part of the surface of hair number 1. It is a small particle (of less than 4μm of maximal length) of elongated form and finely creneledoutlines; its spectrum is mainly constituted of sulphur and barium (barium sulphate), with some little peak of strontium.

The photograph of Figure 27 an other example of barytime sulphate particle deposited on another part of hair number 1 surface. Photographs of Figure 28 show two other examples of particles of barytine located near some part of the hair number 2 and on some part of the hair number surface, respectively.

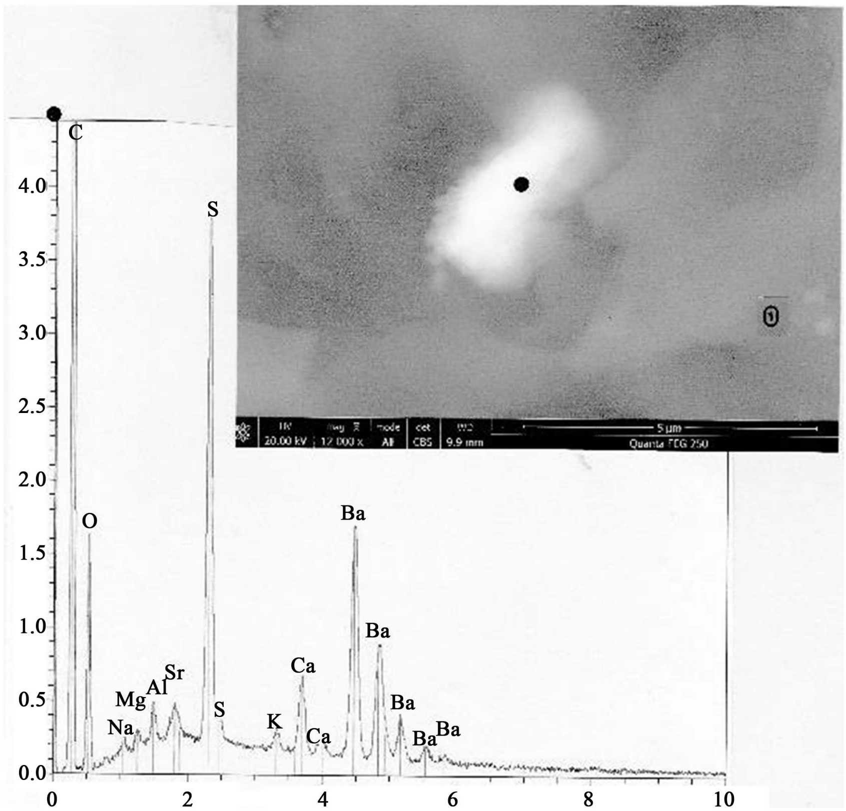


Figure 26. A first example of a barytine particle on hair number 1. *Above*: SEM photograph (in CBS, 12,000×) of the barytine particle, located on a portion of hair number 1. *Below*: spectrum at the black dot. C: carbon; O: oxygen; Na: sodium; Mg: magnesium; Al: aluminium; Sr: strontium; S (two peaks): sulphur; K: potassium; Ca (two peaks): calcium; Ba (five peaks): barium.

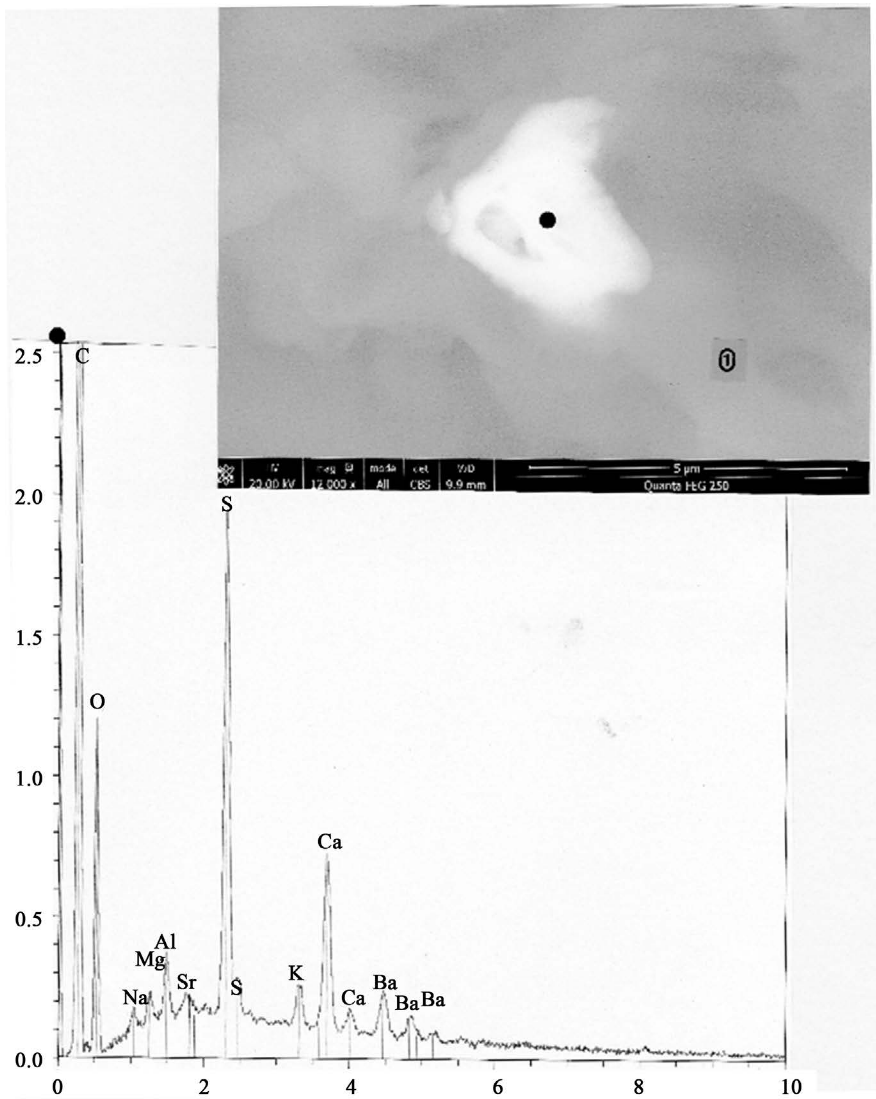
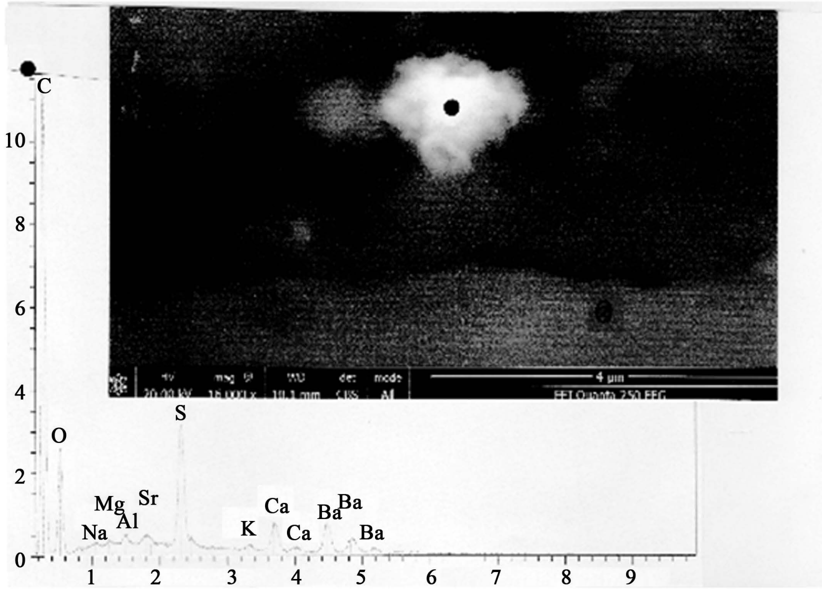


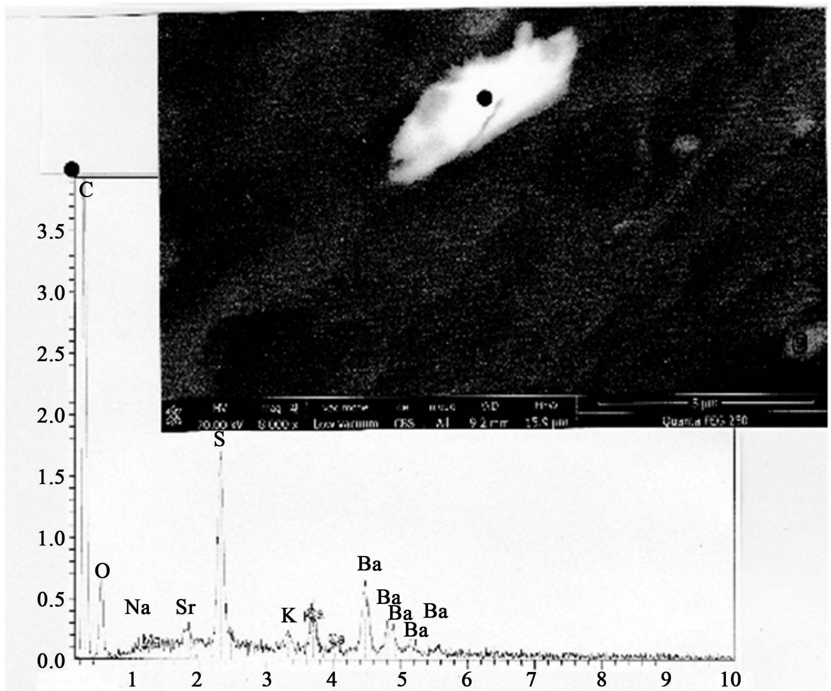
Figure 27. A second example of a barytine particle on hair number 1. *Above*: SEM photograph (in CBS, 12,000×) of the barytine particle, located in another portion of hair number 1. *Below:* spectrum at the black dot.

Table 3 summarizes the numbers of barytine particles we found on the surfaces of the ten hairs studied; we detect such particles on almost all of the hair surfaces. This total number of 86 barytine particles observed is indicative of a prolonged station of the corpse under the ceiling of the cave.

Barytine deposits must not be confused with micro-scales of barium sulphate, the most commonly used white pigments used by painters (often as a found) during the 19th Century. On the photograph of **Figure 3**, we have seen such a particle (that shows some similarities in aspect and dimension with those of barytine), located on some portion of the hair number 3 surface and loaded here as an artefact. The photograph of **Figure 29** shows an example of a micro-trail (of a length of about 3 µm) of such matter, located on some portion of the hair number 2 surface; the corresponding spectrum indicates that it is mainly



(a)



(b)

Figure 28. Third and fourth examples of barytine particles at the vicinity of hair number **2** and on the hair number **9**. (a): upper SEM photograph (in CBS, 16,000×) of the third barytine particle located at the vicinity of a portion of hair number **2**. *Below*: spectrum at the black dot; (b): lower SEM photograph (in CBS, 8000×) of the fourth barytine particle located on a portion of hair number **9**. Below: spectrum at the black dot.

composed of barium sulphate, without strontium (that permits to distinguish it from barytine particles).

The photograph of **Figure 30** shows a relatively voluminous (of about 30 μm of maximal dimension) micro-scale of barium sulphate pigment, deposited on

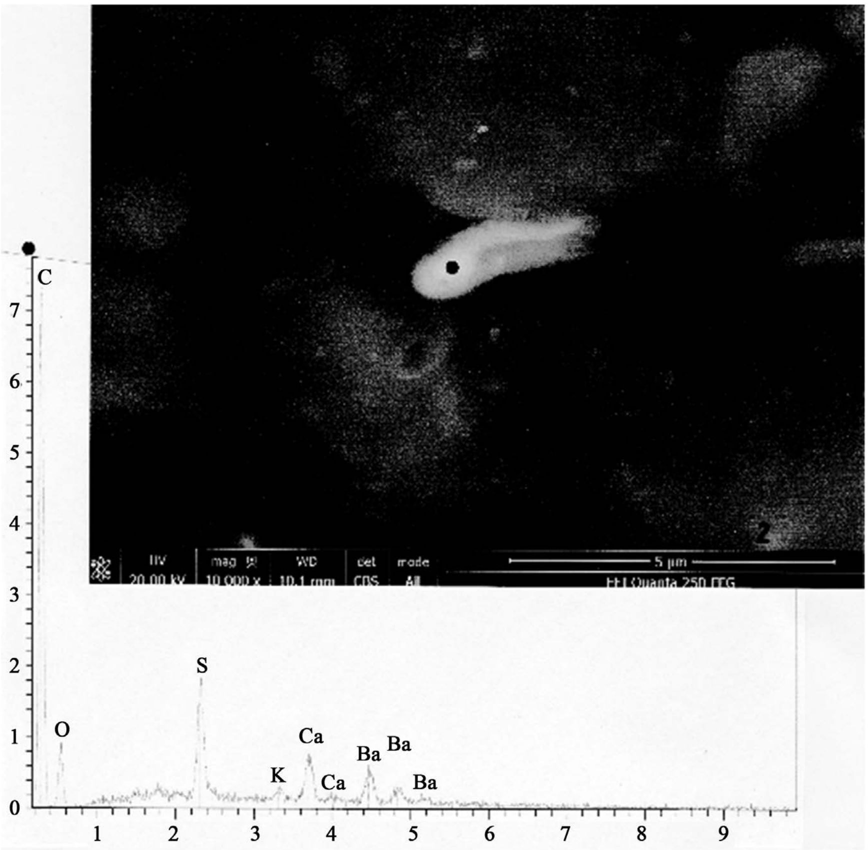


Figure 29. A micro-trail of barium sulphate pigment on hair number **2**. *Above*: SEM photograph (in CBS, 10,000×) of the micro-trail, located at some part of the hair number **2** surface. *Below*: spectrum at the black dot. C: carbon; O: oxygen; S: sulphur; K: potassium; Ca (two peaks): calcium; Ba (three peaks): barium.

Table 3. Numbers of barytine particles found on hairs.

Hair numbers	Numbers of barytine particles found on each hair surfaces	Illustrations
1	18	Figure 26 and Figure 27
2	26	Figure 28
3	9	
4	12	
5	7	
6	4	
7	6	
8	0	
9	4	Figure 28
10	0	

the superior border of some part of hair number 3 surface. Its corresponding spectrum establishes that this pigment is loaded on particles of a synthetic aluminosilicate (with iron) clay, calcium carbonate being used as the charge.

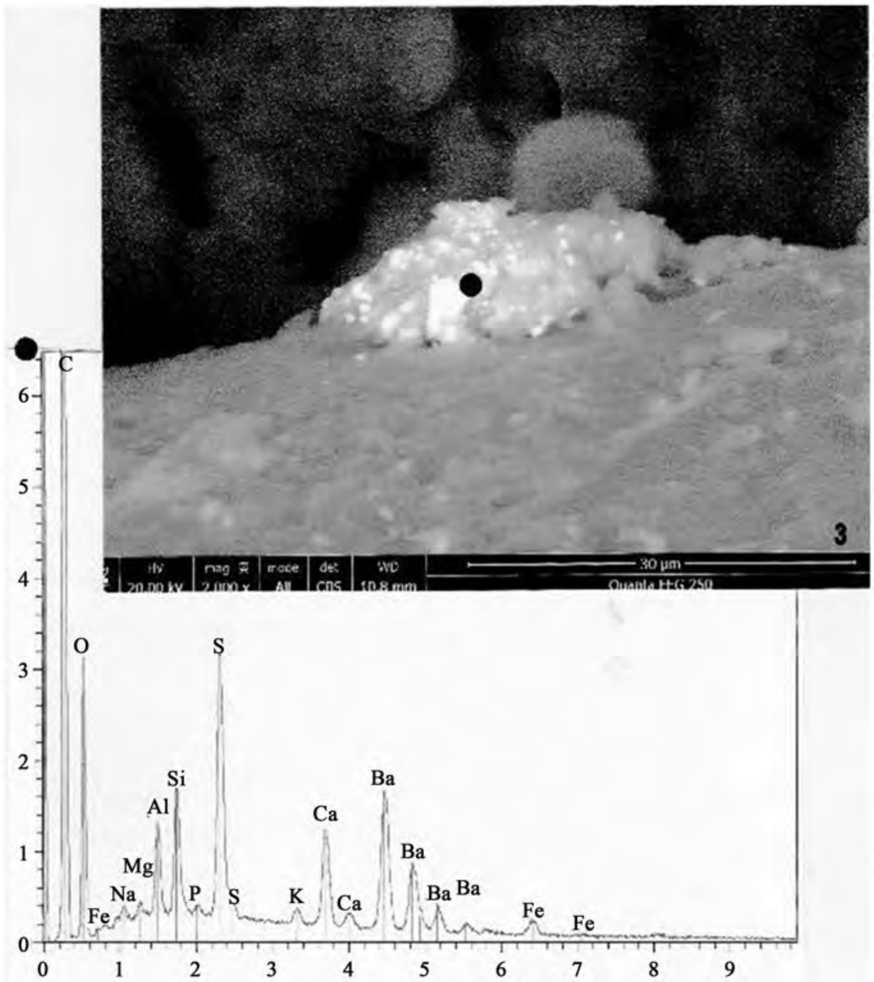


Figure 30. A micro-scale of barium sulphate pigment on hair number **3**. *Above*: SEM photograph (in CBS, 2000×) of the micro-scale, located on some part of the hair number **3** surface. *Below*: spectrum at the black dot. C: carbon; O: oxygen; Fe (three peaks): iron; Na: sodium; Mg: magnesium; Al: aluminium; Si: silicium; P: phosphorous; S (two peaks): sulphur; K: potassium; Ca (two peaks): calcium; Ba (four peaks): barium.

5. Conclusion

We have found numerous micro-remains of marine minerals and micro-organisms at the vicinity or on the surface of Marie-Madeleine's hair studied. This indicates that these hairs are those of a dead body that was in close contact with sea-water. We deduced that Marie-Madeleine was transported by her companions as a dead person in the small boat, like a mummy, during the travel from Palestine to Provençal shores.

Consequently, Marie-Madeleine, contrary to her living companions (particularly Holy Maximin), has not evangelized the Provençal town of Marseilles.

We suspect just as well that it was actually the Marie-Madeleine's cadaver that was exposed facing the sun during thirty years on the top of the Sainte-Baume mountain, and not the living body of Marie-Madeleine ("fed by angels") according to what is said in the "tradition des Saints de Provence".

We have detected many mineral particles of barytine on or near the surfaces of the hairs. These particles originated from the ceiling of the Sainte-Baume cave, where there are the main mineral constituents of the walls. Abundance of these particles on the hairs confirms a prolonged exposure of the body in the cave, during a precedent period to that of the cementing process intended to protect the walls of the cave.

Consequently, many assertions (notably the transport of Marie-Madeleine as a living person from Palestine to Provence coats, her evangelization of the town of Marseilles, and her living during thirty years on the top of the Sainte-Baume mountain) of the "tradition des Saints de Provence" are legendary.

Acknowledgements

We thank the priest of Saint-Maximin-la-Sainte-Baume, who furnished to us Marie-Madeleine's hair. Thank you also to Françoise Sur, President of the Association "Les Amis de la Basilique", who sent us some samples of the walls of the Sainte-Baume cave. Jean-David Malnati is acknowledged for his undefectible financial support.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Charlier, P., Weil, R., Delblock, R., Augias, A., & Deo, S. (2017). Helium Ion Microscopy (HIM): Proof of the Applicability on Altered Human Remains (Hairs of Holy Maria-Magdalena). *Legal Medicine, 24,* 84-85. https://doi.org/10.1016/j.legalmed.2016.12.002

Corliss, J. O. (1979). *The Ciliated Protozoa, Characterization, Classification and Guide to the Literature* (2nd ed.). London: Pergamon Press.

Franzoni, A. (2015). *Sainte Marie-Madeleine et les Saints de Provence dans la tradition Provençale* (Vol. 2). Sainte-Baume: Editions ASTSP.

Grossi, A. (2012). Jewish Shrouds and Funerary Customs (33 p.) *The 1st International Congress of the Holy Shroud in Spain,* Centro Espanol of Sindonologica (CES).

Heimdal, B. R. (1993). Chapter 6 Modern Coccolitophorids. In *Identifying Marine Phytoplankton* (pp. 731-816). New-York: Academic Press.

Lucotte, G., & Thomasset, T. (2017). Study of the Red Colour of Ste Marie-Madeleine (≈3-63) Hair by Scanning Electron Microscopic Characterization of Its Melanosomes. *Journal of Dermatology and Pigmentation Research, 1,* 108-116.

Lucotte, G. (2016). The Mitochondrial DNA Mitotype of Sainte Marie-Madeleine. *International Journal of Sciences, 5,* 10-19. https://doi.org/10.18483/ijSci.1167

Lucotte, G., Thomasset, T., & Salmon, A. (2018). Fennel (*Foeniculum vulgare*) Rests on the Holy Maria-Magdalena's Hairs, Studied by Scanning Electron Microscopy and Elemental Analysis. *Archaeological Discovery, 6,* 216-270. https://doi.org/10.4236/ad.2018.63012

Ludes, B., & Coste, M. (1996). *Diatomées et Médecine Légale.* Paris: Lavoisier.

Steckbach, J., & Kociolek, J. P. (2011). *The Diatom World.* Heidelberg: Springer. https://doi.org/10.1007/978-94-007-1327-7

Travers, A., & Travers, M. (1971). Catalogue des Tintinnides (Ciliés Oligotriches) Récoltés dans le Golfe de Marseille de 1962 à 1964. *Tethys, 2,* 639-646.

Trouillet, M. C. (2016). *Les Reliques de Ste Marie-Madeleine*. Petrus: Aix-en-Provence.

Winter, N. B. (2012). *Scanning Electron Microscopy of Cement and Concrete.* Woodbridge: WHD Microanalysis Consultants Ltd.

Supplementary

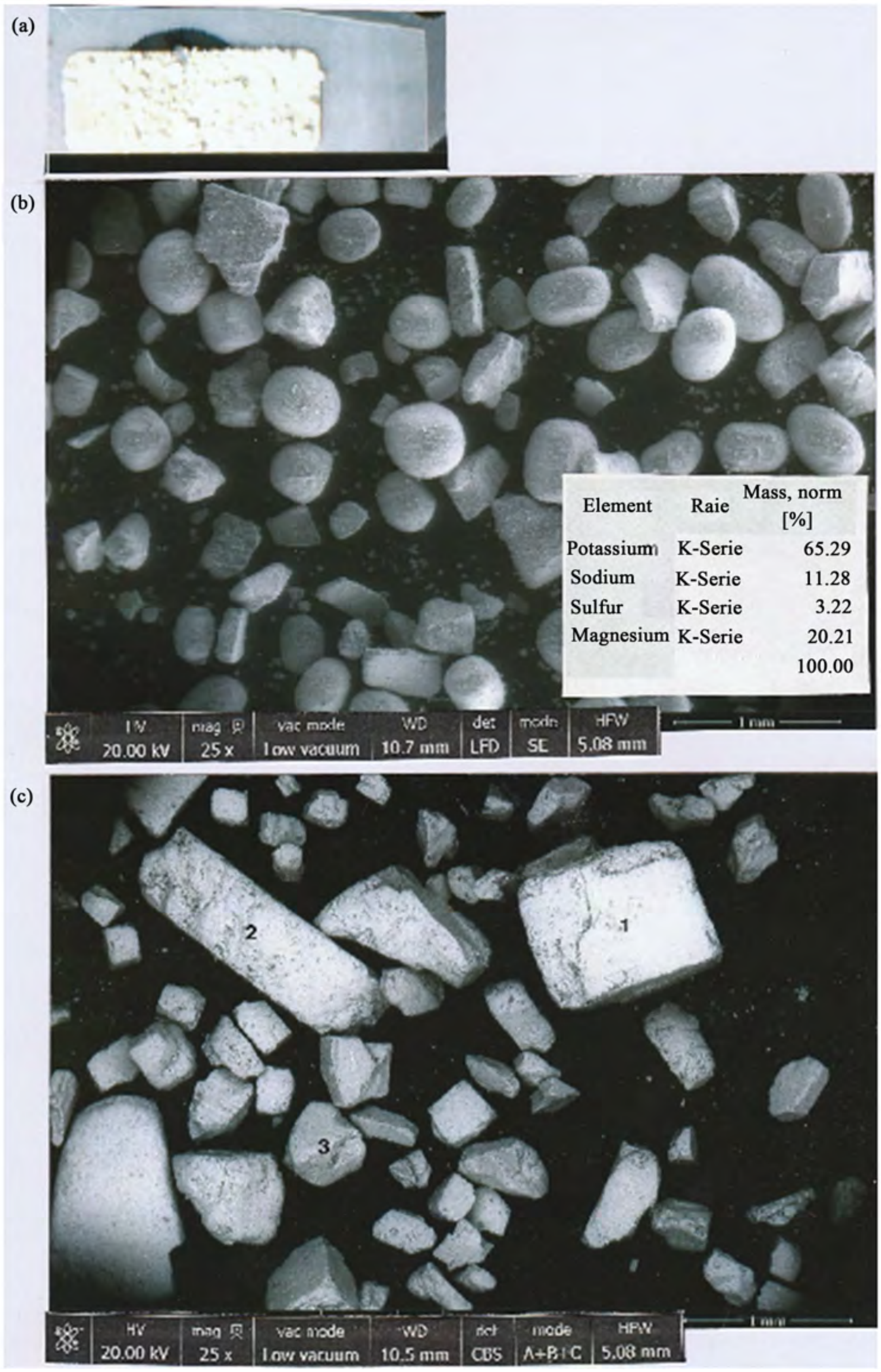


Figure S1. Study of a light salt powder. (a): optical view (2×) of the powde; (b): SEM photograph (in LFD, 25×) of a sample of the powder. Insert: normalized (chlorine excepted) composition of the powder. **C**: SEM photograph (in CBS, 25×) of another sample of the powder. **1**: a sodium chloride (ClNa) crystal; **2**: a potassium chloride (KCl) crystal; **3**: a magnesium chloride ($MgCl_2$) crystal.

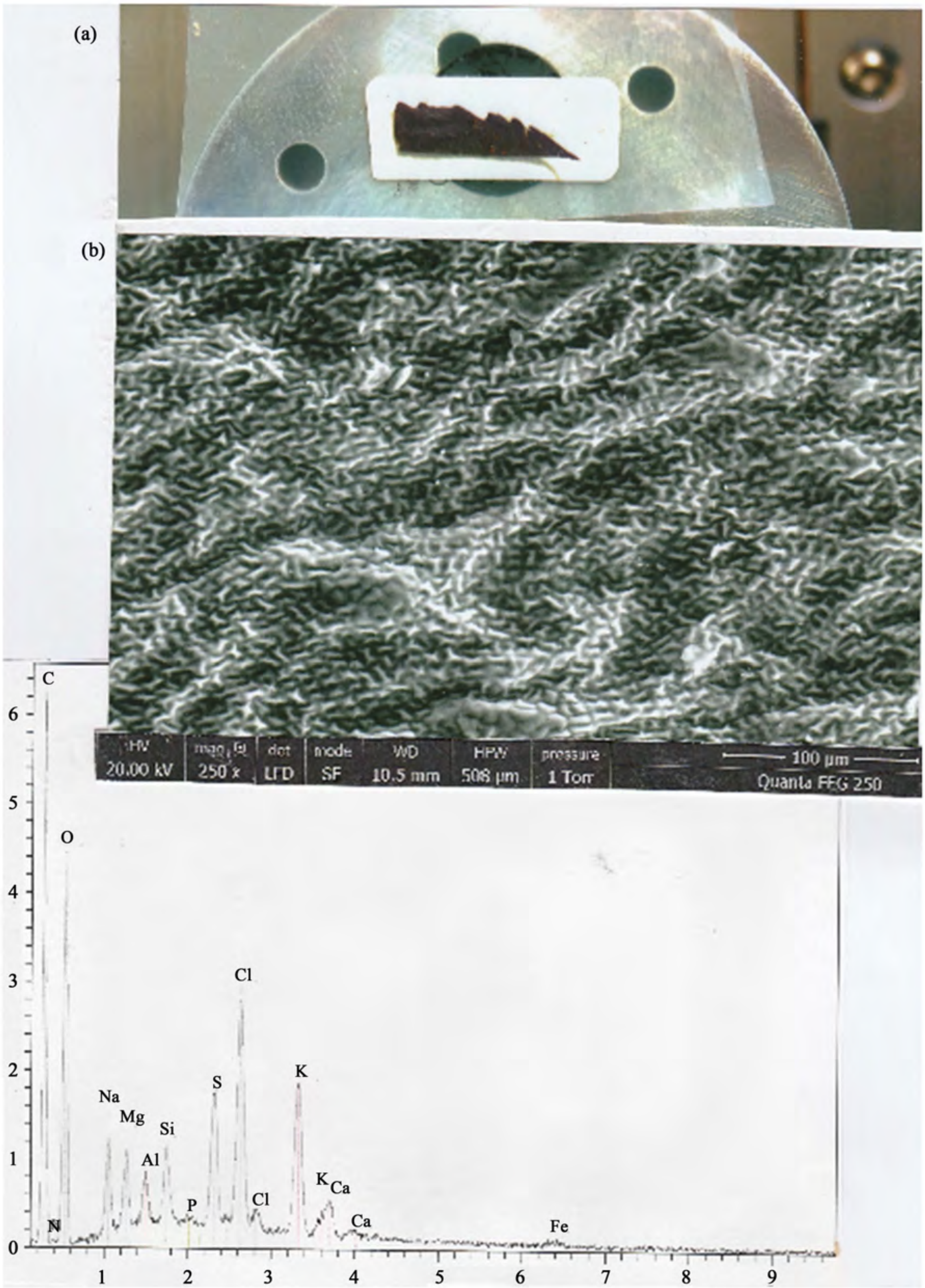


Figure S2. Study of a thalle of *Fucus*. (a): optical view (2×) of a surface portion of the *Fucus*; (b): SEM photograph (in LFD, 250×) of the surface portion; (c): global spectrum of the surface. C: carbon; N: nitrogen; O: oxygen; Na: sodium; Mg: magnesium; Al: aluminium; Si: silicium; P: phosphorous; S (two peaks): sulphur; K (two peaks): potassium; Ca (two peaks): calcium; Fe (traces): iron.

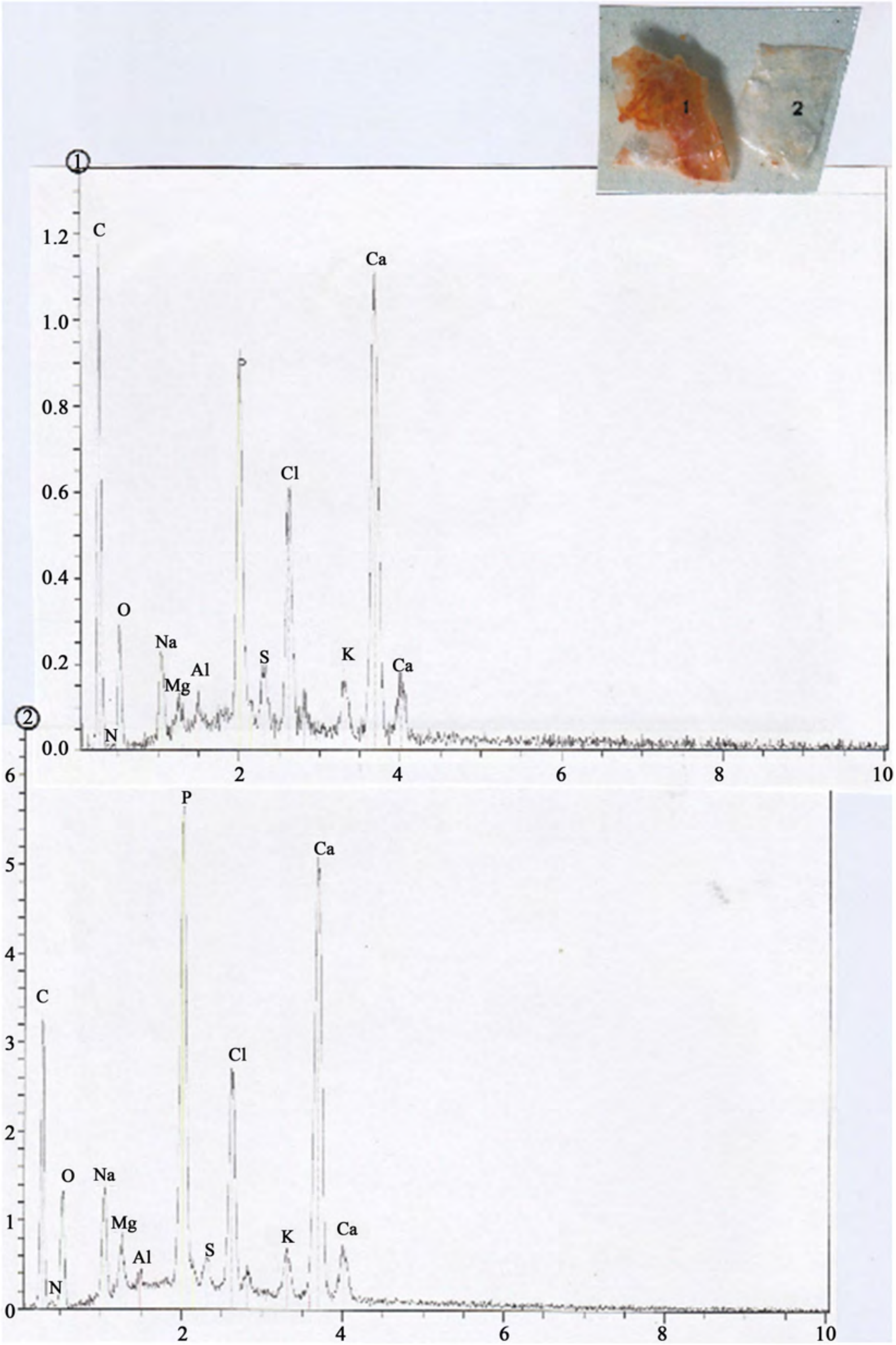


Figure S3. Study of a pawn shell. *Above*: optical view (2×) of the shell. **1**: colored (red) shell fragment (dorsal); 2: white (ventral) shell fragment. *Below*: spectras of **1** and **2**. C: carbon; N (traces): nitrogen; O: oxygen; Na: sodium; Mg: magnesium; Al: aluminium; P: phosphorous; S: sulphur; Cl (two peaks): chlorine; K: potassium; Ca (two peaks): calcium.

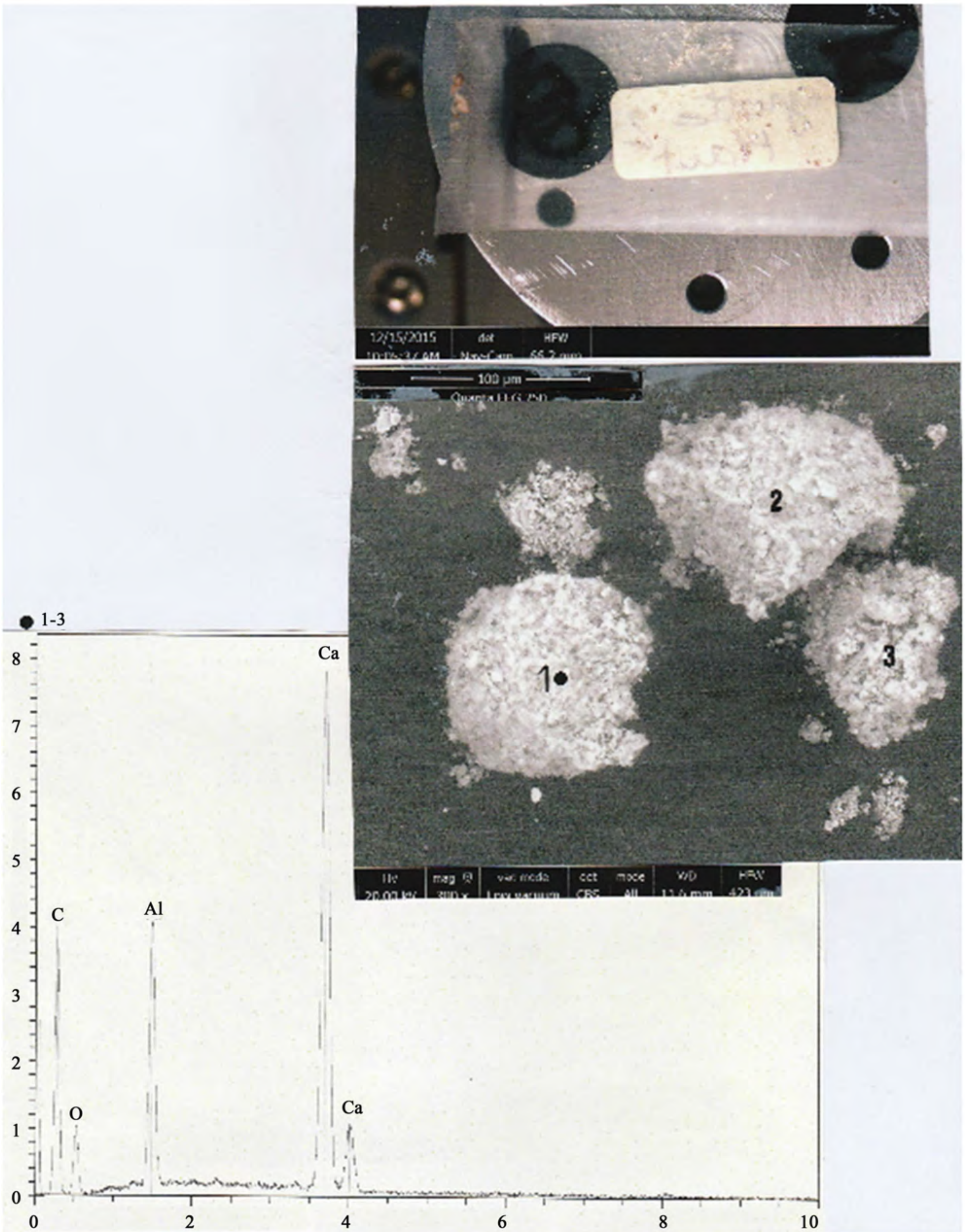


Figure S4. Study of the coating of the ceiling of the cave. *Above:* optical view (2×) of the coating powder. *Below*: SEM photograph (in CBS, 300×) of three (1 - 3) well separated aggregates of the coating. *Spectrum* (at the black dot), that is common to 1 - 3. C: carbon; O: oxygen; Al: aluminium; Ca (two peaks): calcium.

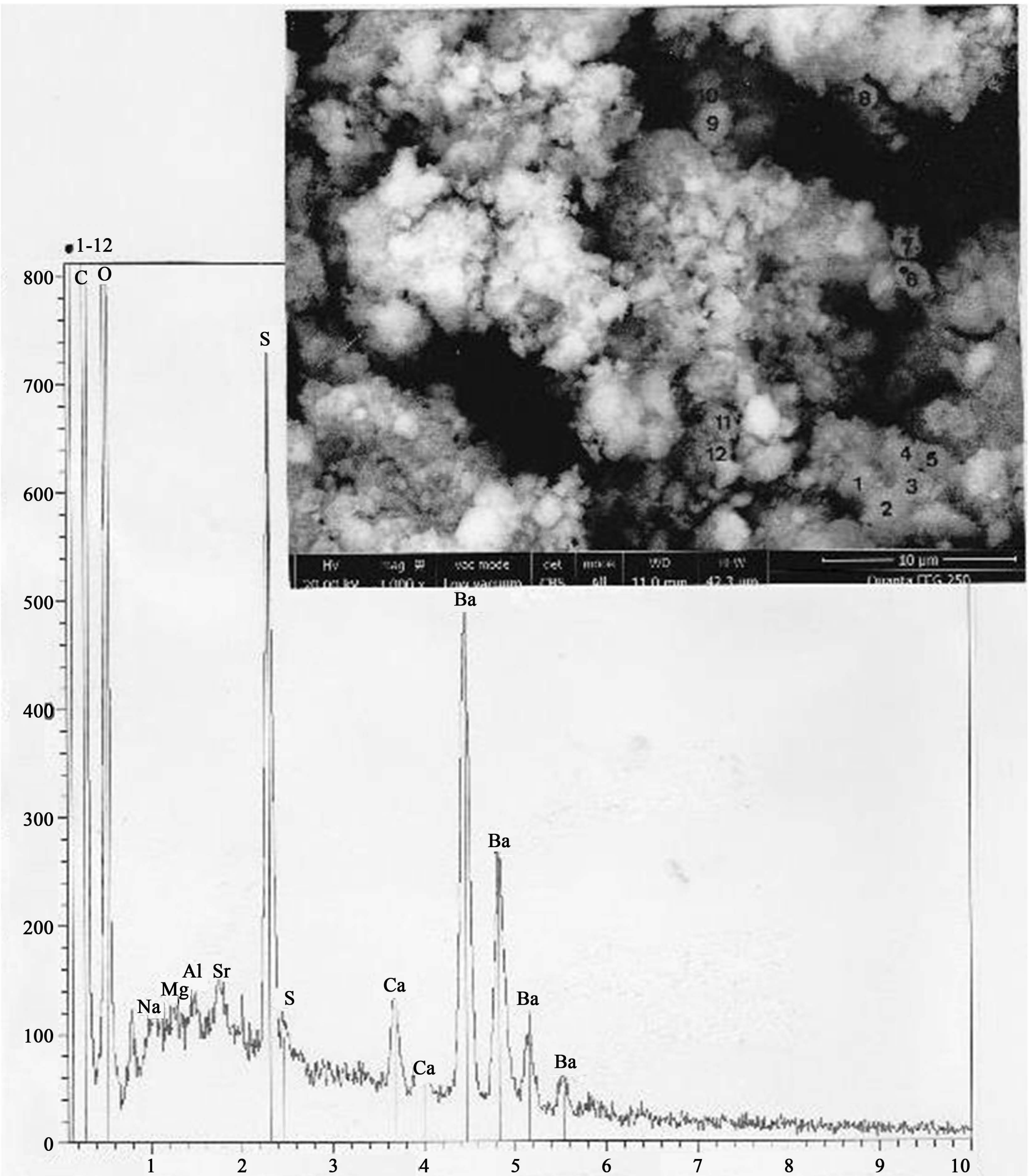


Figure S5. Study of the particles located under those of the coating. *Above*: SEM photograph (in CBS, 3000×) of twelve (1 - 12) particles between those of the coating. *Below*: highly resolutive spectrum at the black dot, that is common to particles 1 - 12. C: carbon; O: oxygen; Na: sodium; Mg: magnesium; Al: aluminium; Sr: strontium; S (two peaks): sulphur; Ca (two peaks): calcium; Ba (four peaks): barium.