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Environmental Degradation of Granite Stoneworks, Karnak Temples, Egypt.

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Abstract: Karnak temples complex is one of the most important archaeological sites in the world. A huge portion of this complex was constructed of granite such as; the colossal statues of Ramses II, Thutmose III, parts of some pylons, and the obelisks. The granite stoneworks at Karnak complex suffer from different deterioration phenomena such as; missing parts, disintegration, exfoliation, contour scaling, cracks and fractures, in addition to different kinds of coatings (crusts, skin, soiling, film or thin layer) such as; dust, dirt, staining and crystallized salts, which lead to aesthetic disfigurement and chemical alterations. Deterioration factors were from different sources such as; changes in temperature, moisture, salts and wind in addition to anthropogenic factors. Studying deterioration factors and their phenomena were performed through different scientific investigations and analyses such as; light optical microscope (LOM), polarizing microscope (PM), scanning electron microscope (SEM), X-ray powder diffraction (XRD), Energy dispersive analysis (EDX).The obtained results have revealed that, the granite stoneworks suffer from crystallization of sodium chloride and calcium sulphate (gypsum) salts in addition to kaolinization and sericitization process.

Key words: Karnak temples, granite, stoneworks, degradation , coating , salts, gypsum , kaolinite.

1. Introduction

The Karnak temples complex is one of the largest temples in the world, and consists of several smaller temples, it's cover an area about 250 hectares. This complex was built during a time about 1500 years. Karnak complex comprises several pylons, colossal statues in addition to obelisks and sanctum; most of those monuments were built of granite. The study is concerned with the granite works belonging to Amenhotep II, Tuthmosis III, Ramesses II, which varied among colossal statues, stelae, obelisks and parts of Pylons **(1)**. Granite is one of the famous and the oldest ornamental stones that were widely utilized in many of the most impressive monuments and buildings in the world and ancient Egyptian civilization, the popularity of granite in the monumental buildings is attributable to its a good polish due to its greater hardness, its appearance and also its resistance to weathering **(2)**. Aswan was the main area for quarrying granite in ancient Egypt; the quarries cover an area about 4-5 km and the amount of rose-granite mined in this region is hard to estimate but is likely to be in the range of some million tons **(3)**. During Egyptian history the Aswan granite was the third most

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important stone utilized for different purposes, after sandstone and limestone (4), in terms of quantities, its largest use was reached during the Old Kingdom, particularly associated with the 4th Dynasty pyramid complexes at Giza, when 45.000 cubic meters of stone were removed from the quarries of Aswan (5), and again during the New Kingdom for obelisks and colossal statues (6).From at least the early Dynastic until Greco-Roman periods the ancient Egyptian employed granite in their buildings and architectures in different ways such as; External and internal wall veneer on pyramids, linings of burial chambers and passages in pyramids and mastaba tombs, door lintels, jambs, thresholds of temples, temple columns, platforms, basins, barque shrines, small statue shrines (naoi), obelisks, offering tables, small vessels, sarcophagi, stelae, small to colossal statues (7). Despite the importance of granite stone works in Karnak temples complex, there is no detailed study concerned with their deterioration. So, this paper discusses the environmental deterioration and degradation of those monuments.

1.1. Conservation state

The huge granite stoneworks at Karnak temples such as; obelisks, colossal statues were carved from one piece of stone (large monolithic) without using mortar, the stability of those monuments is attributed to the gravity load, contact pressure in addition to the corresponding shear friction action between the heavy monumental stones (8).For a long time the granite stoneworks at Karnak temples were vulnerable to numerous deterioration and degradation factors in different environments such as; burial and aerial environments, in addition to internal deterioration factors which related to the whole properties of granite rock, while the aerial or exogentic factors include the extreme variations in temperature, solar radiation, moisture, wind, rain in addition to anthropogenic factors. The anthropogenic deterioration factors is varied in granite stoneworks at Karnak temples and represented in reusing, sunderance and moving of those monuments such as; the reusing of the colossal statues of Ramesses II by Ramesses III, Ramesses VI, Sethos II and Pinedjem, also the reusing of the eastern obelisk and colossus statue of Thutmosis III by Ramesses III (9). Also the sunderance (cutting off) and re-shaping the upper part of the eastern stela of Amenhotep II which lies before the southern side of the Eighth Pylon **(Fig.1(a))** as large millstone (to crush the grains) during the Ptolemaic or the Roman times and now preserves at the Shutb magazine at Assiut Governorate (10). In addition to moving the western obelisk of Thutmosis III, in front of the seventh pylon to Constantinople (11).The other factors of human deterioration represented in the quick discovery together with the sudden exposure for granite stoneworks from under-ground to aerial environment, that cause the environmental shock (12). In addition to using un appropriate materials for restoration **(Fig.1(b))**. The environmental factors such as wind and rains could lead to the wet & dry deposition

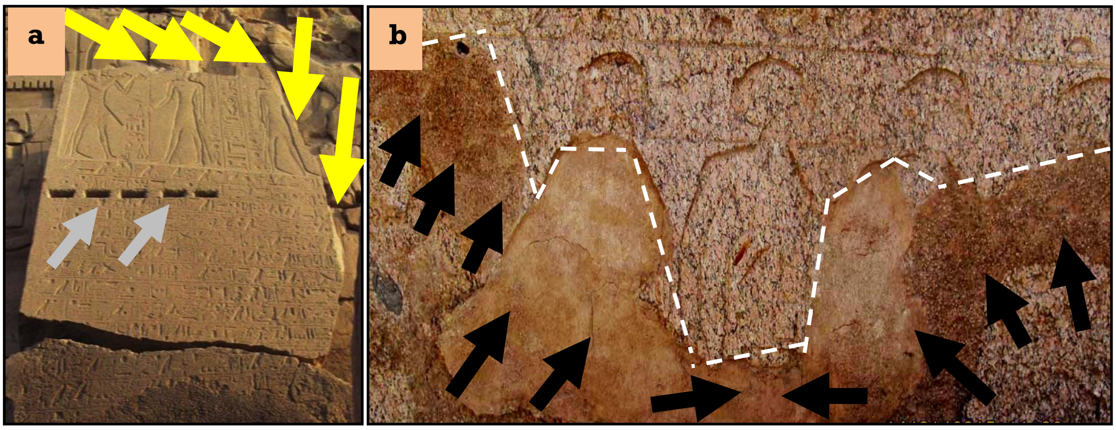

Figure.1. Deterioration features of granite stoneworks at Karnak temples; (a) Cutting parts and splitting marks in stela of Amenhotep II. **(b)** Restoration with un appropriate mortar.

of different pollutants (13) which react with granite stoneworks and cause the formation of the different altered surface layers (14) or coatings such as dust, soot and thick layers of hard crusts **(Fig.1(c))**, which lead to aesthetic disfigurement and roughness of the surfaces (15).Also the rainfall leads to dissolution of the wind-blown particles and causes the defacement of the hue, value and chroma (16) of granite stoneworks in the shape of vertical lines **(Fig.1(d))** and white precipitates on the surfaces(17). Generally, the granitic rocks are characterized with heterogeneity and anisotropy in mineralogical composition (18) so, the cracks will occur depending on its mineralogy and fabric during uniaxial cyclic loading and start at cleavage planes and in the grains boundary contact which finally lead to the formation of fractures **(Fig.1(e and f))** under the compressive loads **(19)**. Furthermore there are several granitic colossal statues and obelisks at Karnak temples were collapsed either partially or totally losing **(Fig.1(g))** as victim to the earthquakes **(20)** particularly in the state of soil liquefaction after floods events **(21)** and the existence of cracks and fractures in their textures which cause

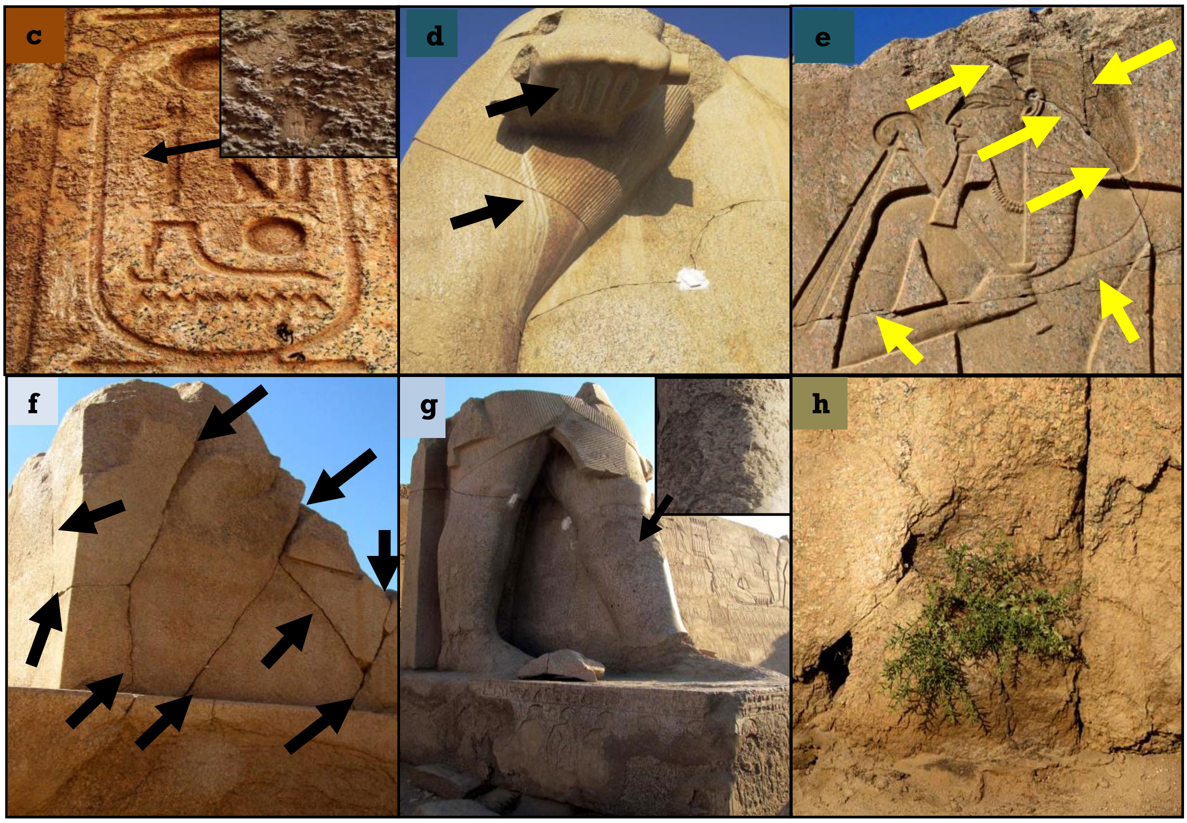

Figure .1.Deterioration features of granite stoneworks at Karnak temples; **(c)** Thick coatings of soiling. **(d)** Soiling by rains. **(e)** Cracks. **(f)** Fractures network. **(g)** Missing parts and roughness. **(h)** Plant growth.

the stiffness of the structure and decrease the material mass. On the other hand the variation of temperature plays a vital role in enhancing those discontinuities in those monuments. The ground water and saline solutions attack the granite stoneworks through their discontinuities and the result is the growth of plant vegetation **(Fig.1 (h))**, chemical weathering of the main constituents such as mica and feldspars minerals which lead to the formation of clay minerals, surface roughness and pitting **(22)**,**(23)**, in addition to the discoloration and staining by iron oxides **(Fig.1(i))** and crystallization of salts. Furthermore the surface heterogeneities and microenvironment (microclimatology) cause a significant deterioration phenomena such as; cracks, exfoliation **(Fig.1(j))** and contour scaling **(24)** and also, the soiling by bird droppings was recorded (**Fig.1(k))**.

Figure.1.Deterioration features of granite stoneworks at Karnak temples; **(i)** Staining and contour scaling. **(j)** Exfoliation. **(k)** Birds droppings.

2. Materials and Methods

Weathered samples were collected from granite stoneworks at Karnak temples and studied by different scientific methods such as light optical microscope (LOM), polarizing microscope (PM), scanning electron microscope (SEM) and X-ray diffraction (XRD) to identify their mineral composition, morphological features and alteration products.

3.Results

3.1.Light Optical Microscope (LOM) investigation

Stereomicroscope images have illustrated that, the granite has granular texture, with different sizes of mineralogical grains mostly coarse and cracked **(Fig.2 (a))**, and the mineralogical components have coloured grains and spots of iron oxides which stained the grains with brownish colours **(Fig.2 (b))**, hereto most of the samples contain a high amount of black mica minerals (biotite) **(Fig.2(c))**,which exfoliated as thin flakes (micro scales) due to deterioration factors**(Fig.2(d))**.The investigation showed also that, the granite has several deterioration features such as; dust and soiling skin attached with the surface which caused roughness of the surface and disfigurement the color and appearance of granite **(Fig.2(e))**.The other features in the samples represented in inter-granular fractures (fractures between grains boundaries) due to the weakness and de-cohesion among mineralogical grains of granite, trans-granular or intra-fractures (fractures inside individual grain) **(Fig.2(f and g))**, those fractures and cracks help the water and saline solutions to penetrate inside, the result is that; the wideness and enlargement both kinds of those discontinuities, crystallization of different salts **(Fig.2 (h))**, which lead to aesthetic disfigurement and cause the degradation and damage the granite through disconnect, dislocation and loss of the mineralogical grains and rupture of granite's texture **(Fig.2(i))**.

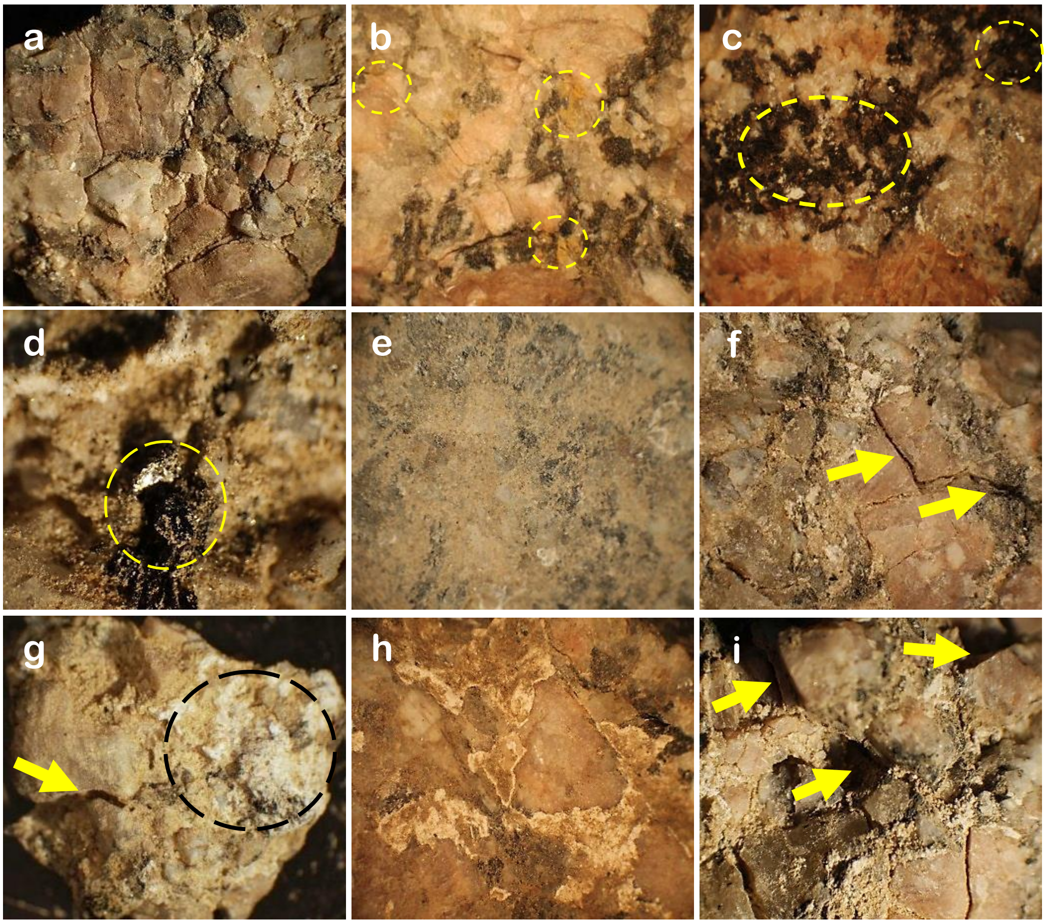

Figure.2.Micrographs of investigated weathered granite samples by LOM (4X); (a) Coarse and cracked grains. **(b)** Spots of iron oxides. **(c)** High amount of mica. **(d)** Micro scales of exfoliated mica. **(e)** Dust and soiling skin. **(f)** Intra-granular cracks. **(g)** Dilated fracture and salts . **(h)** Hard crust of gypsum. **(i)** Loss of mineralogical grains.

3.2. Petrography

The investigation of the deteriorated samples of granite by utilizing polarizing microscope **(Fig.3 (a-j))**, shows that; the rock is composed mainly of sodic feldspars (plagioclase), quartz, biotite, alkali feldspars as essential minerals, while zircon, allanite, garnet and opaque are accessories. Sericite and kaolinite represented the secondary minerals in the studied samples due to some alteration processes such as sericitization and kaolinization.

Plagioclase is represented by albite which occurs as subhedral to anhedral prismatic elongated crystals. It is characterized by albite twinning with slightly deformation. Furthermore plagioclase shows varied degrees of alteration to sericite, the rime of the plagioclase crystals is still fresh while the core is altered to sericite displaying oscillatory zoned **(a** and **b)** .The plagioclase crystals are impregnated with iron rich minerals**(i)** sometimes, plagioclase shows corrosional boundaries against quartz and biotite **(c** and **d)**.

Myrmikite texture **(e)** is common in the studied granite; it forms vermicular intergrowths of quartz with phenocrysts of altered plagioclase. Ghost myrmikite is defined as plagioclase-vermicular-quartz intergrowth occurring in rocks lacking K-feldspar **(25)**.

Alkali feldspar is represented in orthoclase and occurs as subhedral tabular crystals, slightly kaolinitized.

Quartz occurs as subhedral to anhedral crystals exhibit undulose extinction and have serrate boundaries. Quartz occurs as the interstitial crystals between the other crystals of the studied granite, or as the veinlets cutting the other minerals **(h)**.

Biotite is one of the mafic minerals reflexing the main dark component in the studied granite. It has a perfect and pleochroism flakes and easily to split up into thin flexible sheets. In the studied thin sections, biotite occurs as anhedral to subhedral flakes, strongly pleochroic from a dirty, dark olive brown to pale yellowish olive or yellowish brown.

The flakes of biotite are altered to iron oxhydroxides or oxides; the replacement generally starts along the periphery of the flakes and extends irregularly toward the center of the mineral. The PM investigation detects weak undulose extinction in individual biotite due to subsequent mechanical stresses.

Zircon and fluorite are abundant in the biotite flakes, which commonly exhibit pleochroic halos **(c** and **g)**.Zircon is characterized by high relief, colorless and rimmed by iron oxides. Sometimes, zircon crystals are fractured and metamicted with pleochroic haloes due to radiation damage from the radioactive inclusions **(f)**.

Allanite occurs in the form of small idiomorphic crystals, often with a clearly marked zonal structure, colors varying from yellow- brown to red-brown or dark honey yellow colors depending on its zonal arrangement with a light to dark pleochroism when the microscope stage is rotated, exhibit zoning at their rims **(j)**.

The cerium-epidote allanite is particularly remarkable minerals, which feature in Aswan granite; it mainly occurs the crystals of allanite are up to 2 mm in size.

Allanite most often develops the radiogenic haloes in conjunction with the adjacent minerals biotite and hornblende.

Garnet occurs as grains or crystals associated with biotite, it is characterized by high relief and dark brown colors in plane light, sometimes occurs as isolated grains in different shapes and some of them are perforated by quartz grains **(h)**.

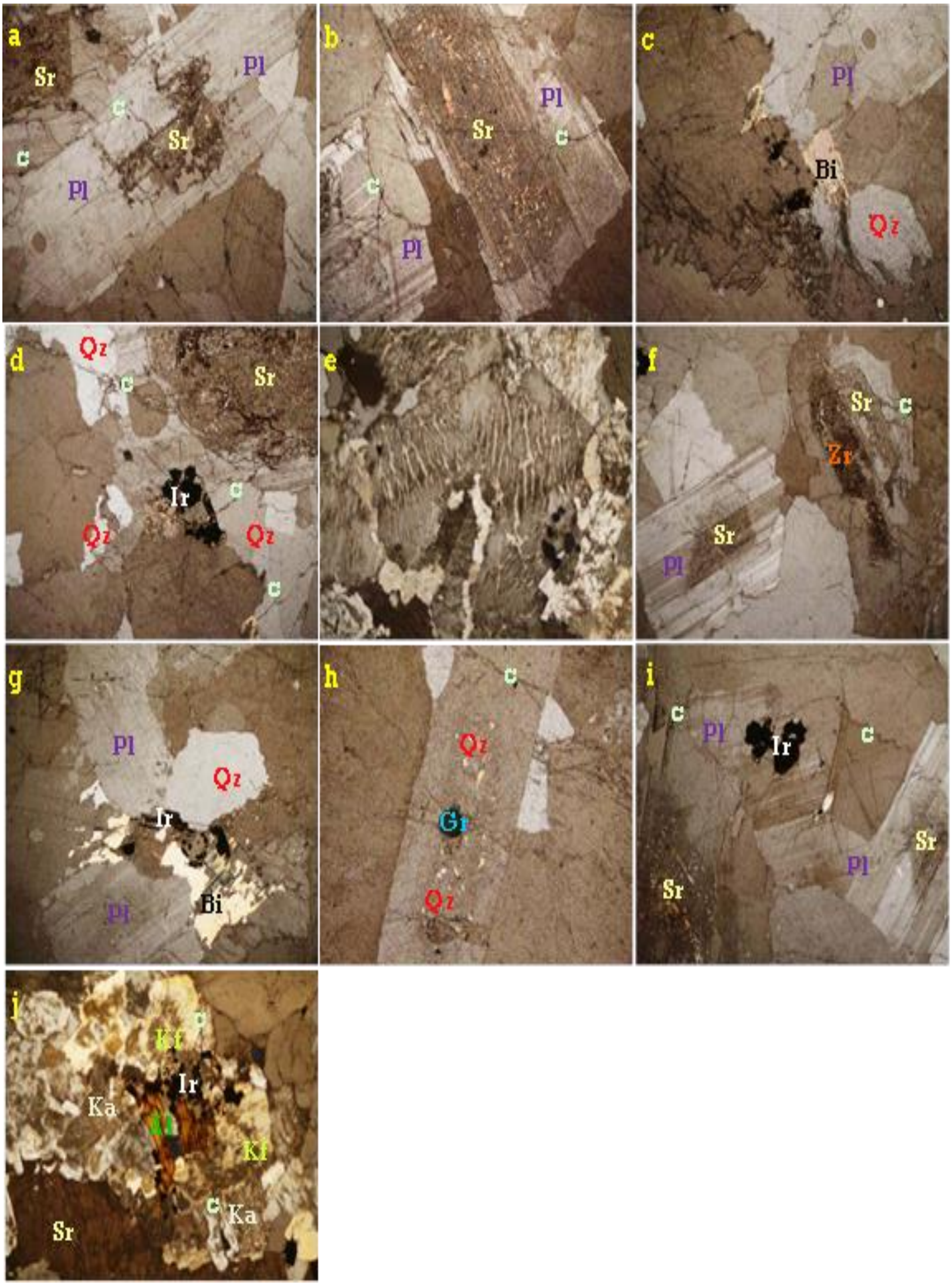

Figure.3. Petrographical micrographs of granite from Karnak temples showing ; (a & b) Altered plagioclase (Pl), strongly sericiteized (Sr) . **(c)** Quartz (Qz) and biotite (Bi) . **(d)** Cracks in quartz (c) and iron oxides (Ir) . **(e)** Myrmikite texture . **(f)** Metamicted zircon (Zr) . **(g)** Biotite altered to iron oxides . **(h)** Garnet grain (Gr) inside vein of quartz . **(i)** Iron oxides stained plagioclase. **(j)** Allanite (Al) and K- feldspar (Kf) altered to kaolinite (Ka) .

3.3. Scanning Electron Microscope (SEM) Investigation

The investigation of some weathered samples of granite stoneworks at Karnak temples evinced that, the granite surfaces covered with thick film or coating comprises of different and various substances include soot, dust and dirt particles in addition to silica grains, other wind-blown particles and dead insects like spiders **(Fig.4 (a)**).The salinity of the soil and ground water assist the deterioration of granite stoneworks through the growth of the plants in lower parts, near the ground so, their roots penetrate inside the granite structure **(Fig.4(b))** which lead to the degradation process **(26)** and evolution the large and deep cavities **(Fig.4(c))**. Furthermore the growth of fungal hyphae **(Fig.4(d))** and other microbial species, the growth of those microorganisms in addition to chemical solutions caused the damage of granite and decomposition of its components especially feldspars in different degrees; to range from slightly altered to strongly altered **(Fig.4(e))** and formation the clay minerals (kaolinite) at the end **Fig.4(f and g))**.More than that different kinds of salts such as sodium chloride and calcium sulphate phases such as gypsum and anhydrite **(Fig.4 (h and i))** were crystallized in the texture of granite due to the previously mentioned reasons and/or the saline solutions and lead to disintegration of granite.

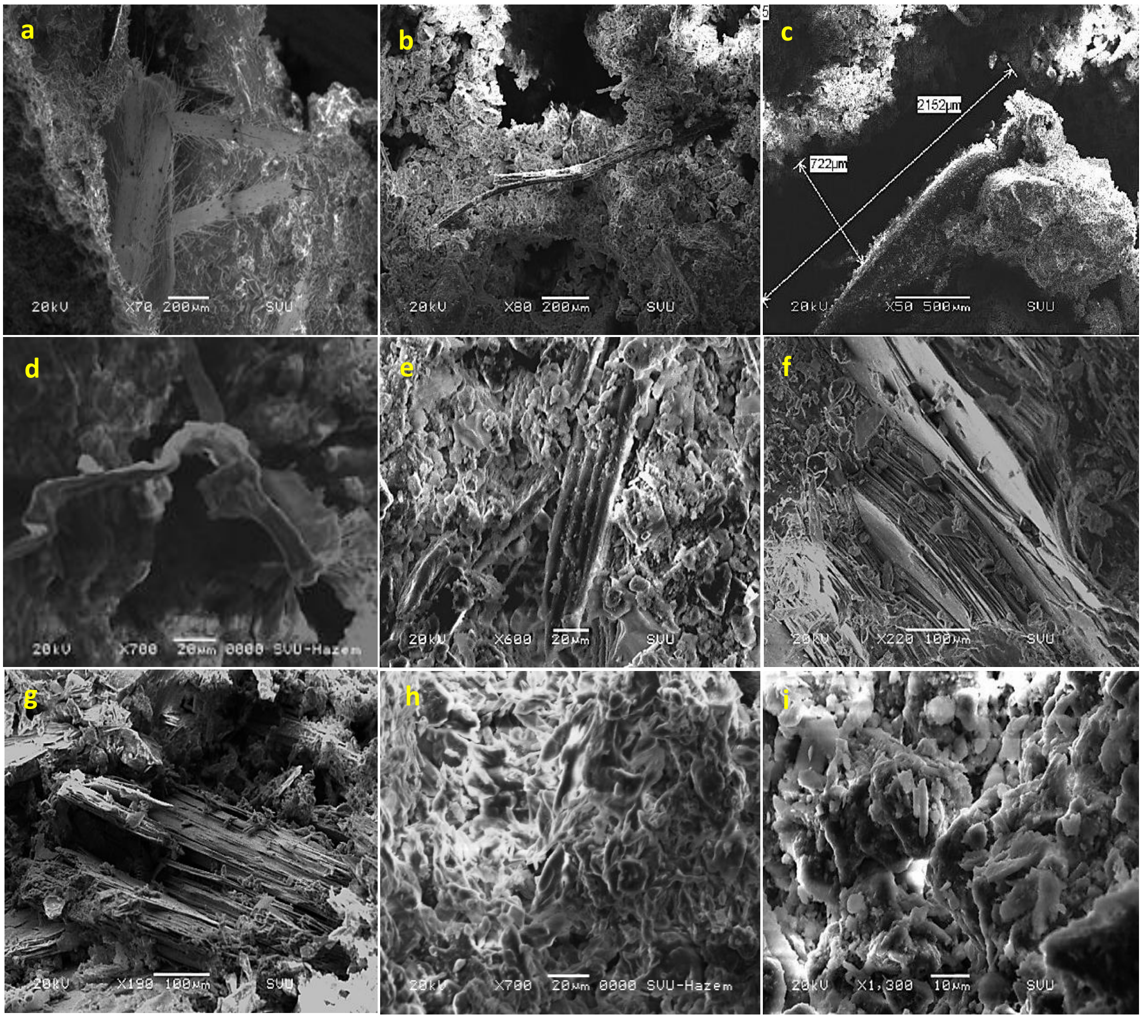

Figure.4. SEM micrographs of granite samples from Karnak temples; **(a)**Dead insect. **(b)** Plant roots . **(c)** Deep cavities. **(d)**Fungal hyphae **(e)** Weathered feldspars. **(f and g)** Kaolinite. **(h and i)** Salts (sodium chloride and calcium sulphate).

3.4. X-Ray Diffraction analysis (XRD)

Some deteriorated samples from granite stoneworks at Karnak temples have been analyzed by X-Ray Diffraction analysis (XRD) to find out their mineralogical composition and alteration products shown in **(Fig. 5(a-f)** and **Table (1))** as the following;

The results point out that granite composes essentially of quartz SiO_2 (48.38%) and biotite $K(Mg,Fe)_3 AlSi_3O_{10}(OH)_2$ (11.86%) the most abundant minerals of all samples. The other minerals in granite represented in sodic feldspars such as albite $NaAlSi_3O_8$ (17.18%) and potash feldspars or microcline $KAlSi_3O_8$

(13.22%).While the alteration products represented in halite NaCl (3.73%), kaolinite $Al_2Si_2O_5(OH)_4$ (2.62%) and gypsum $CaSO_4.2H_2O$ (2.33%),furthermore the granitic samples revealed less ratio of anhydrite $CaSO_4$(0.55%) and calcite $CaCO_3$.

Table.1 Results of XRD analysis of studied samples.

Sample No	quartz	albite	microcline	biotite	calcite	kaolinite	gypsum	halite	anhydrite
a	68.5	23.7	1.5	6.3	-----	-------	--------	-------	--------
b	47.4	26.8	17.9	7.2	0.7	------	------	-------	-------
c	29.5	16.8	46.6	3.3	------	3.8	------	------	-----
d	39.8	32.6	------	16.8	------	2.2	8.6	-----	------
e	59.9	3.2	13.3	21.3	-----	------	------	2.3	-----
f	45.2	-----	------	16.3	------	9.7	5.4	20.1	3.3
Total	**48.38**	**17.18**	**13.22**	**11.86**	**0.12**	**2.62**	**2.33**	**3.73**	**0.55**

4. Discussion

Granite was one of the most important ornamental stones used in the ancient world particularly ancient Egyptian civilization, so it was employed by ancient sculptors and architects for different purposes. A great portion of Karnak temples complex was erected using granite such as colossal statues, obelisks and pylons, which are susceptible to different types of deterioration such as internal, external environmental and anthropogenic deterioration factors cause varied deterioration phenomena such as coatings, exfoliation, fractures, salts crystallization and collapse.

LOM investigation of weathered granite samples has cleared that, granite contains very coarse grains of quartz and feldspars, high amount of biotite, the samples include various types of cracks, fissures and fractures among and inside of the grains. In addition to mixed coatings of dust, dirt and crystallized salts.

Petrographic study: The investigated thin-sections of the studied granite at Karank temple showed that the rock texture is mainly granular and coarse- grained, composed mainly of plagioclase, quartz, biotite and potash feldspar, in addition to zircon, allanite, garnet and opaque are accessories. The secondary minerals in the studied samples are represented by sericite and kaolinite. The plagioclase and potash feldspar followed by biotite are the most susceptible primary minerals to alteration due to the effect of chemical weathering and saline solutions dominating in the microenvironment. The plagioclase is partially and completely altered to sericite which is emphasized by networks of transverse and some irregular longitudinal cracks. Also the transformation of K-feldspar to kaolinite in diverse degrees, biotite also was altered to iron oxides which cause stains or patches of a blood red to black pigmentation to the grains of stone, this pigmentation due to the degradation of the iron bearing minerals such as iron oxides. The thin sections revealed also that, the stone contains an appreciable portion of cracks and corroded borders in the grains of quartz which attributed to the effect of mechanical and chemical weathering.

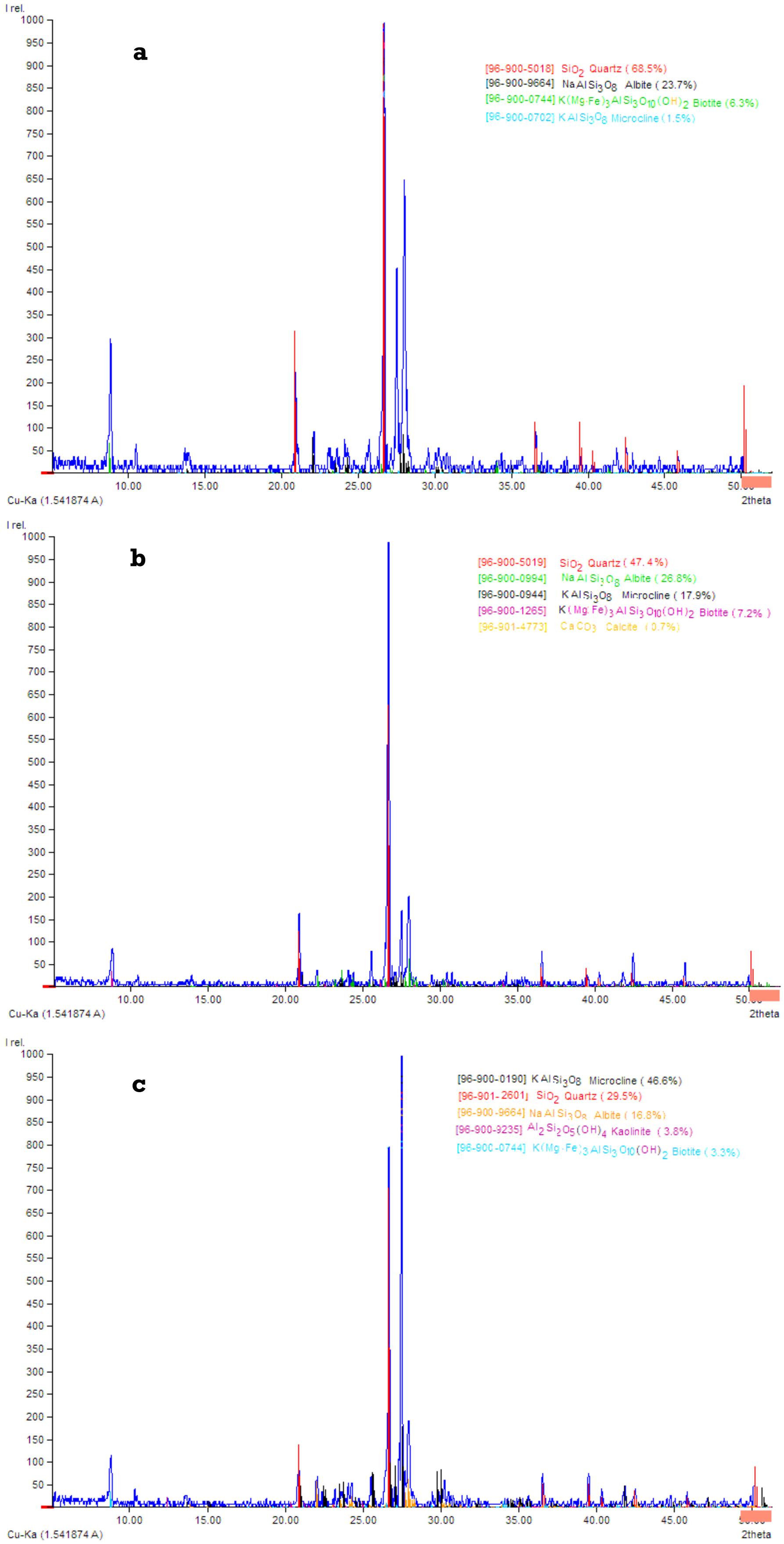

Fig.5.XRD patterns of granite samples from Karnak temples.

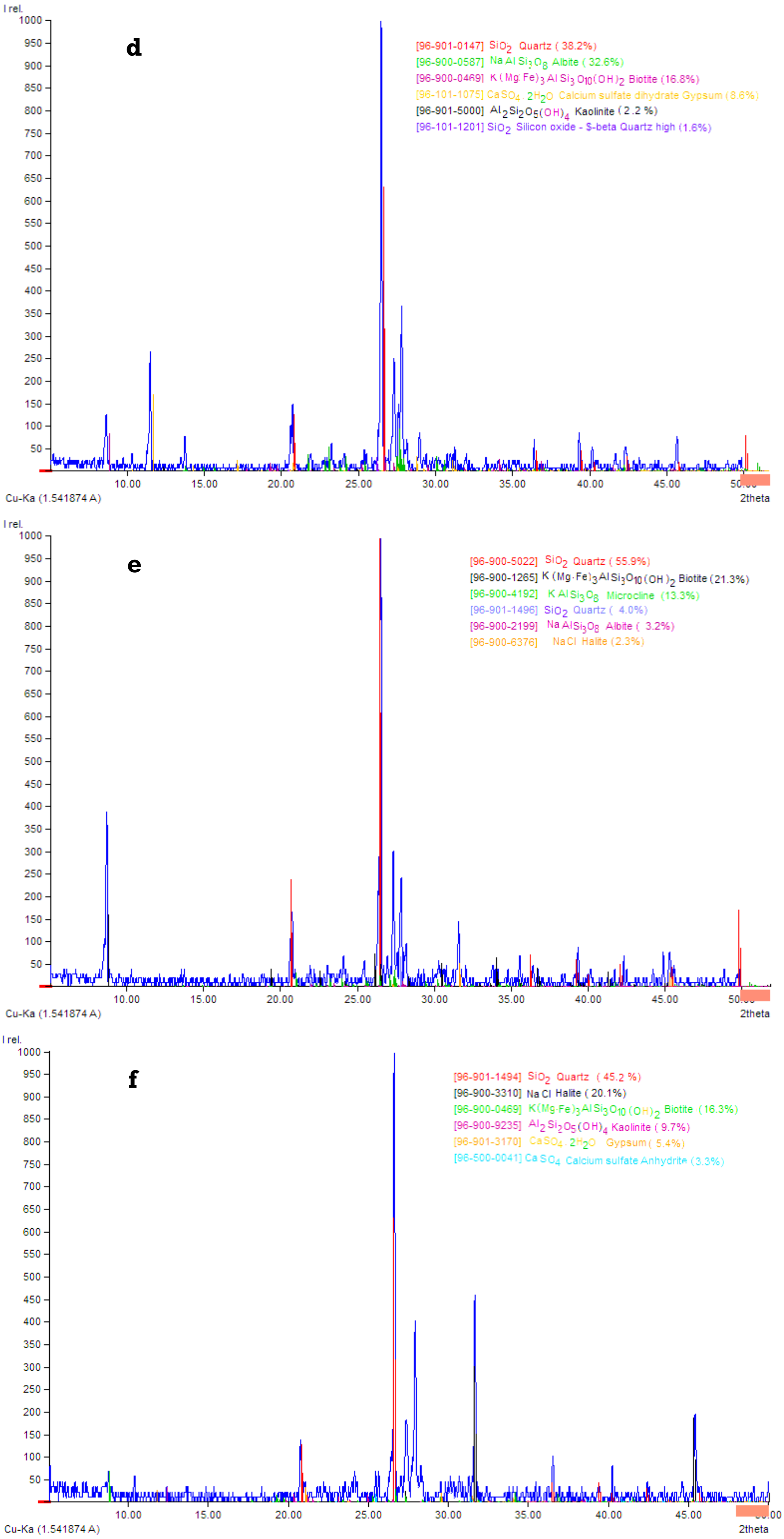

Fig.5.XRD patterns of granite samples from Karnak temples.

SEM investigation has revealed that, the superficial stratum of granite samples contains mixture of varied substances and wind-blown particles such as dirt, dust, soot and silica grains in addition to dead insects like spiders embedded in the previous mixture. The morphology of interior and sub- strata of the samples illustrated vast cavities contributed to the migration of soluble salts and aqueous solutions and extension plant roots inside the structure of granite. The SEM showed also that, the growth of fungal hyphae, that with saline solutions play a vital role in the degradation and the alteration of mineralogical grains of granite especially feldspars to clay minerals; kaolinite which is emphasized also by XRD analyses. On the other hand a high amount of crystallized salts such as sodium chloride, gypsum and anhydrite were detected through the SEM.

XRD studies have showed that, granite consists mainly of quartz SiO_2 and biotite $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$ as the main constituents in all studied samples, the other components in most of granite samples represented in feldspars minerals such as albite $NaAlSi_3O_8$ and microcline $KAlSi_3O_8$.The XRD analysis identified a lot of neo-formed minerals as alteration products such as halite NaCl, kaolinite $Al_2Si_2O_5(OH)_4$, gypsum $CaSO_4.2H_2O$, anhydrite $CaSO_4$and calcite $CaCO_3$.The halite salts are attributed to the ground water and also it's very common salt in Egyptian soil, while the existence of calcite is due to the decomposition of feldspars minerals as a result of the chemical solutions effects, calcium is concentrated in the plagioclase feldspars; albite, anorthite and mafic minerals which are released and mobilized during the early stages of chemical weathering. In the same manner calcite reacts with sulphate ions dissolved in the soil and forms calcium sulphate dihydtate or gypsum. The latter transforms to calcium sulphate dehydtate due to the effect of high temperature at the site. On the other hand, the feldspars minerals such as albite and microcline react with carbon dioxide CO_2 dissolved in ground water or water vapor to form clay minerals or kaolinite through kaolinization process according to the following equations (27):

$$2\,NaAlSi_3O_8 + 3H_2O + 2CO_2 \longrightarrow Al_2Si_2O_5(OH)_4 + H_4SiO_4 + 2Na\,HCO_3$$

Albite	water	carbon dioxide	Kaolinite	Silicic acid	Sodium bicarbonate

$$2\,KAlSi_3O_8 + 3H_2O + 2CO_2 \longrightarrow Al_2Si_2O_5(OH)_4 + H_4SiO_4 + 2K\,HCO_3$$

Microcline	water	carbon dioxide	Kaolinite	Silicic acid	Potassium bicarbonate

Furthermore, SO_2 from air pollution plays a dual role in the weathering of granite (28) through the acceleration the kaolinization process of feldspars and formation of gypsum salts.

Recommendations

1. Extraction the salt by a two-layer-poultice consists of (25% cellulose + 45% bentonite + 30% diatomaceous earth) and silica mixed with water (29).
2. Removal of sodium and sulphate salts by cheap, moderate, easy and effective poultice based on sepiolite clay, and CMC (30).
3. Removal of staining by iron oxides (red coating) by cleaning the surface by poultice 10 % EDTA dissolved in acetone (31).
4. Paving the temple floors with flagstones to reduce the dust resulting from the visitors' passage (side walk).
5. Strengthening and stabilizing the weak granite stoneworks using appropriate chemical consolidants with ethyl silicate-based products (32) such as; Wacker OH as well as Paraloid B 72 (31), or the ethyl silicate modified with a methyl-phenyl resin (33). Recently a lot of consolidants such nanotechnology based water repellent find a wide range in consolidation weathered granite (34).
6. Measuring the cracks with crack meter to determine their state.
7. Assembling the separated fragments of granite stoneworks with an appropriate type of epoxy and steel bars.
8. Establishing informative signs and low fences around granite stoneworks as protective procedures.
9. The removal of all deteriorated and ancient mortars and replacing them with a new suitable mortars.
10. Removal of plant vegetation mechanically and chemically.
11. Proceeding a detailed geological study on the granite stoneworks to determine their quarries that helps in the conservation process.

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