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Environmental impact and natural hazards on Kharga Oasis monumental sites, Western Desert of Egypt

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ABSTRACT

Kharga Oasis monumental sites are important to the cultural heritage in the South Western Desert of Egypt. These sites are scattered on the floor of the oasis representing ancient civilizations. The studied sites include the Hibis, El-Nadura, El-Ghueita and El-Zayyan temples as well as El-Bagawat Cemetery. The present study found that natural hazards have remarkable impacts on these sites. The impact of weathering processes, encroachment of sand dunes, stability of foundation beds and shallow groundwater seepage were documented. The present study found that humidity, temperature, sunlight and water content conditions seem to be favorable for biodegradation as evidenced by the presence of algae, bat blood and bird excretions. The radioactivity levels at the investigated sites are also measured via gamma-ray spectrometry.

Sand dunes in the area pose a serious natural threat to the monumental sites. Active sand dunes are rapidly encroaching upon the components of these monuments, partially covering some monuments such as El-Ghueita Temple. These dunes load wind storms with fine sand particles. This causes wind erosion through sand blasting of these sites. Some monuments, such as El-Nadura, El-Ghueita and El-Zayyan temples were constructed on a suitable hard sandstone ground, whereas others, such as the Hibis Temple, were constructed on unsuitable soft shale ground in relatively topographically low area. The impact of the unstable foundation and shallow groundwater levels have caused severe structural damage as evidenced by tilted columns, cracked walls and salt-crystal growth in the porous building stones. These destructive elements threaten some other temples in Kharga Oasis and will eventually cause total physical collapse. Although rain is rare in this area, it can form a real threat to mud brick monuments such as El-Bagawat Cemetery. The natural radioactivity sources resulted in an annual effective dose equivalent values averaging 0.20, 0.13, 0.09 and 0.07 mSv/year for the monumental sites at Hibis, El-Nadura, El-Ghueita and El-Zayyan, respectively.

1. Introduction

The Western Desert covers approximately 700,000 km^2, which are more than two-thirds of the total area of Egypt. The significant oases in the Western Desert are Siwa, Bahariya, Farafra, Dakhla and Kharga. Kharga Oasis is the southern one in this cluster of depressions and represents an important feature in the Western Desert (Fig. 1). It is bounded by the Eocene limestone plateau from the east and north, where steep cliffs form a sharp boundary to the depression floor (El-Sankary, 2002). This limestone plateau stretches along Middle and Upper Egypt with an elevation of up to 550 m above the sea level and about 400 m above the depression floor at the study area. However, towards the south and west, the depression floor merges gradually into the Nubia Sandstone open desert. Geomorphologically, the landscape is considered as either high plateau in the northern and eastern boundaries, or low-lying depression floor, meanwhile the pediment areas in-between, are considered as badlands.

Kharga Oasis is characterized by tropical arid climate. The maximum day time temperature fluctuates within a wide range, reaching up to 45–50 °C in summer months, meanwhile in winter, the minimum temperature may drop to as low as zero at night. Kharga Oasis is known as the driest area in the Eastern Sahara and probably the driest region on Earth (Kehl and Bronkamm, 1993). Wind speed tends to be low in August; it increases progressively in November to January and reaches a peak from March to May causing dust storms famously known as "El-Khamasin". The annual mean value of relative humidity is about 39%. Generally, the atmospheric precipitation as rainfall is extremely scarce and

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Fig. 1. Location map of Egypt showing Kharga Oasis area.

insignificant (~1 mm/year). Although rain is very scarce, occasional heavy rainstorms severely attack the area from time to time, where rainwater might flow for short distances as sheet flash-floods causing damage to villages and roads. The last rainy event took place in the year 1993, where Kharga-Assiut and Kharga-Dakhla roads suffered significant damage (El-Sankary, 2002). The potential environmental impacts of rainstorms are obvious due to absence of drainage outlets in the depression area. The oasis domestic and agricultural water is obtained from springs and wells dug into the underlying porous Nubia Sandstone. Thermal springs at Bulaq and Nasser villages to the south of the city of Kharga are famous with water temperature of up to 43 °C.

Monumental sites are widespread in most of the Kharga Oasis area (Cassandra, 1999). The largest and best preserved site at the Kharga Oasis is the temple of Hibis from the Persian period (660–330 BC), located at about two kilometers to the north of the modern city of Kharga (Fig. 2a). This temple was restored several times in the last century and suffered from a locally rising water table. It is dedicated to the Theban triad, consisting of the Gods Amun, Mut and Khonsu (Cruz-Uribe, 1986), whose relief's are in very good shape. Three kilometers away, the early Christian El-Bagawat Cemetery is located (Fig. 2b), which contains 263 mud-brick chapels with Coptic murals, including the Chapel of Peace with images of Adam and Eve. This site might be considered the oldest major Christian cemetery in the world, dating back to the 4th century AD.

Along the Kharga Oasis, many of the Roman fortified settlements are situated strategically on hilltop sites such as El-Nadura, El-Ghueita, El-Zayyan and Qasr Dush, which incorporate temples and ruins of ancient large communities of people and/or garrison towns. Most of these chains of fortresses lie close to the road crossing the oasis. Most likely, they facilitated the development of agricultural colonies depending on groundwater resources. El-Nadura temple site (Fig. 2c) is located just to the north of El-Kharga city and was built by the Romans either during the rule of Antonius Pius or Hadrian. The temple may have been dedicated to the spouse of Amun, and it is in ruin. This temple is about 700 years younger than Hibis Temple, and belongs to the 2nd century AD. El-Ghueita, a fortified settlement (Fig. 2d), is located about 18 km to the south of El-Kharga city on the crest of a sandstone hillock. From there it commands a strategic view over the desert peneplain. This site includes El-Ghueita Temple, which dates back to 522 BC, and the Temple of Amenebis. Finally, El-Zayyan site (Fig. 2e) includes El-Zayyan Temple.

Naturally occurring processes such as atmospheric, geologic, biologic and anthropogenic processes continually threaten monumental sites worldwide. Remediation can be performed and preventative measures can also be provided in some cases. Remedial action in such cases involves characterization and prediction of such harmful processes, if possible. Furthermore, emergency prevention control or shelter, restoration, re-building or redeployment of the impacted monumental sites is of great importance. In the present study, environmental assessment of the monumental sites surrounding areas and natural hazard impacts on these sites are assessed. Deterioration features are documented and proposed mitigation methods are considered. Environmental radioactivity is assessed through radionuclide activity concentration measurements in the exposed bedrocks, soils and building materials. These

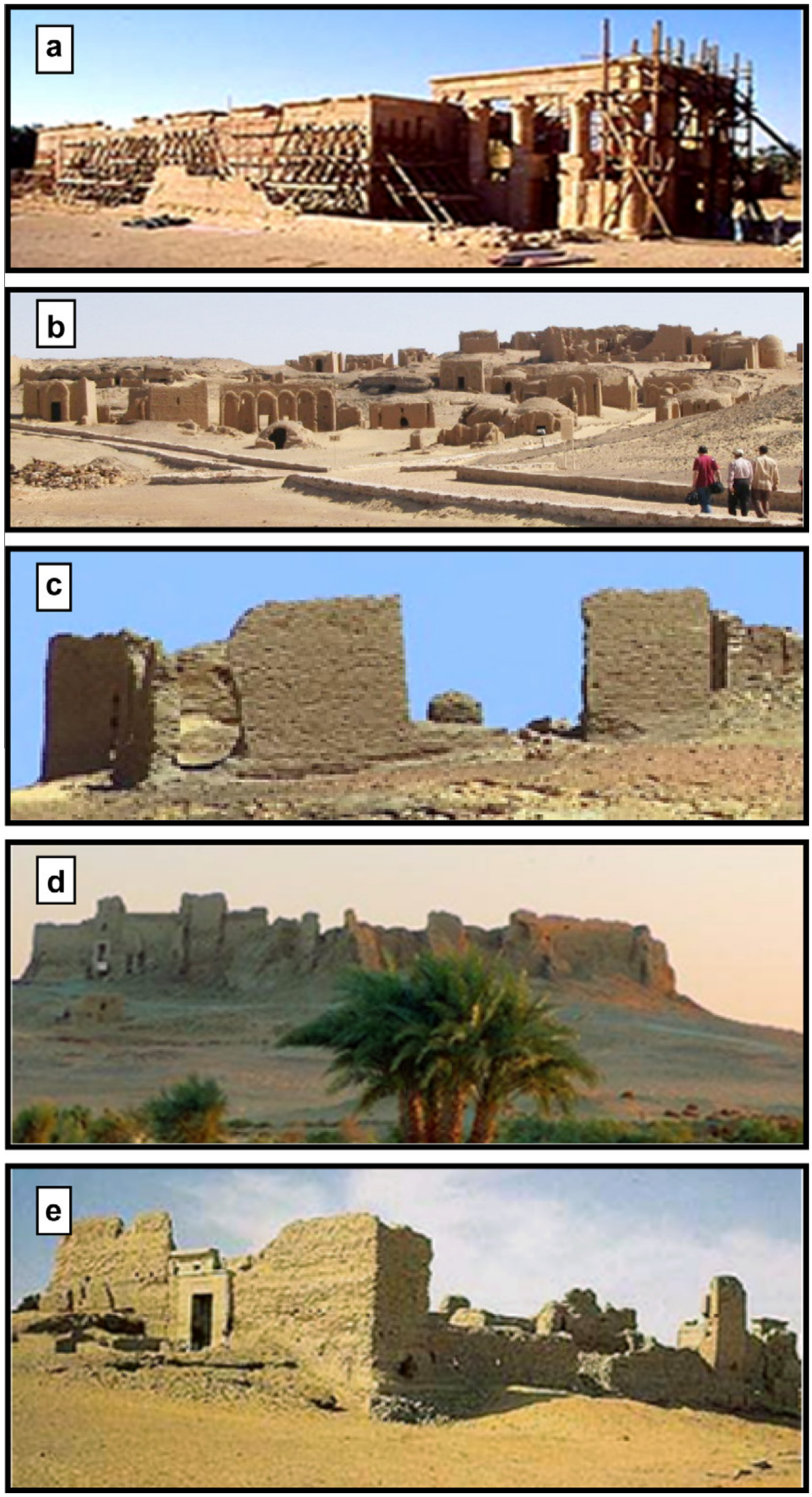

Fig. 2. Panoramic view of the reinforced Hibis Temple (a), El-Bagawat Cemetery (b), El-Nadura fortress (c), El-Ghueita fortress (d), and El-Zayyan fortress (e).

preventative measures are viewed from the preservation perspective of an important part of humanity's cultural heritage.

2. Methodology

Satellite images of Kharga Oasis area and its vicinity have been interpreted to construct a surface geologic map in the light of the available topographic maps, previous geologic works and field investigations. Regional and detailed geomorphologic features of the area have been characterized from satellite images and aerial photographic controlled mosaics compiled from aerial photographs of scale 1:50,000 by Aero Service Corporation and followed up by field investigations.

Rock samples from a large number of stratigraphic sections, various bedrocks, building stones and fallen depresses from the monuments were collected. Representative samples were selected for the detailed petrographical and mineralogical study. The Petrographic study was performed on 29 thin sections prepared with special care to avoid mineral alterations. Six subsurface core samples were collected representing a borehole drilled in the Hibis Temple site with a total depth of 14 meters. Selected samples were subjected to X-ray diffraction analysis to identify their bulk and clay mineralogy. Deterioration features in the monumental sites were documented and the durability and resistance against natural, mechanical and chemical weathering parameters were assessed.

In order to measure the radioactivity levels in surface bedrocks, soils and building materials of the investigated monumental sites, a portable four-channel stabilized gamma-ray spectrometer model Scintrex® (GAD-6) was used. A Scintrex® (GSP-4S) stabilized sensor with a crystal volume of 358 cm^3 of a thallium-enriched sodium iodide (NaI) was used in combination with the spectrometer. Radioelement concentrations were recorded as potassium in percent (K%), equivalent uranium (eU in ppm) and equivalent thorium (eTh in ppm) after background and stripping corrections.

The studied geologic features, field observations and laboratory results were employed in an integrated manner to serve the purposes of the present research with special emphasis on the natural hazard impact assessment on the studied monumental sites.

3. General geology

The geology of the Western Desert, including Kharga Oasis, is very well documented in Knetsch and Yallouze, 1955; Said, 1962, 1990; Issawi and El-Hinnawi, 1982; Salman, 1984; Salman et al., 1984; and El-Hinnawi et al., 2005. From the geologic point of view, the Upper Cretaceous-Lower Tertiary sedimentary sequence overlies nonconformably the Precambrian basement rocks. This sedimentary sequence comprises the Nubia Sandstone overlain by the Variegated Shale rock units, which are well exposed forming most bedrocks of the depression floor. These widely exposed rock units are followed upward by the Duwi, Dakhla, Tarawan, Esna and Thebes formations exposed on the eastern and the northern scarps bounding the depression. This sedimentary sequence includes different varieties of sandstone, shale and limestone with heterogeneous physical and mechanical properties. Furthermore, the Quaternary times in the study area were characterized by alternating periods of wet and dry climates, which resulted in several fluvial, lacustrine and aeolian deposits strewn on the depression floor (Beadnell, 1933; El-Sankary, 2002).

The Upper Cretaceous Nubia Sandstone at Kharga Oasis is a highly dissected, laminated and cross-bedded unit. It is generally composed of alternating sets of relatively coarse and fine grains, which shows marked heterogeneity and different geotechnical characteristics leading to the observed differential weathering (Fig. 3a). This unit is composed entirely of quartz (quartz arenite) with trace amounts of feldspar and rock fragments (Abd El-Whab, 1999). Quartz overgrowth, silica and calcite cements are the most important diagenetic features. $\delta^{18}O$ of the silica cement suggests that it was deposited by meteoric water. The Fe-oxide cement (~2.3%) took place later and suggests an extensive meteoric water invasion in the oxidizing zone. During chemical weathering, gypsum and barite were sometimes precipitated either within the sandstone beds or within the overlying Variegated Shale beds (Fig. 3b and c). Also, minor barite–celestite mineralization (desert roses) occurs along parts of the recorded faults near El-Bagawat Cemetery. Pre-cement porosity versus cementation indicates that about 76% of the destroyed porosity was lost by compaction and the remaining 24% was lost by diagenetic cementation. The present-day porosity of the exposed sandstones is about 28% with significant positive correlation with permeability ($r = 0.86\%$).

Active sand dune belts are the most important Quaternary sediments in the Kharga Oasis and represent a dangerous threat as they occupy widespread, mostly inhabited areas. They are mainly of barchan type of as much as 15 m in height, 200 m in length and 150 m in width (Fig. 3d), which develops distinct morphological features. These dune belts (Fig. 4) are considered part of the southern extension of the great sand dune called Ghard Abu Moharik (Embabi, 2004). Smaller barchan dunes, sand sheets and sand heaps are also frequent in the inter-dune areas. These dunes are formed by the prevailing northerly to northwesterly winds. Movement of such dunes is the most serious obstacle for the cultivated lands in this area. Many efforts have been made to solve the problem of dune migration using parallel groups of reed fences or

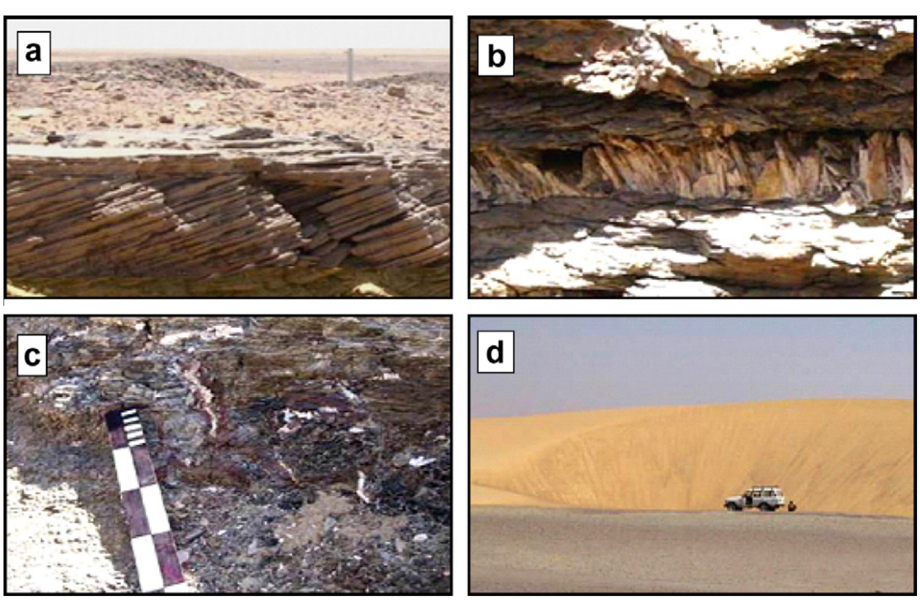

Fig. 3. Field photographs showing cross-bedded sandstone (a), gypsum vein in shale beds (b), bedrock of varicolored shale (c) at El-Bagawat Cemetery site, and a sand dune to the east of the study area (d).

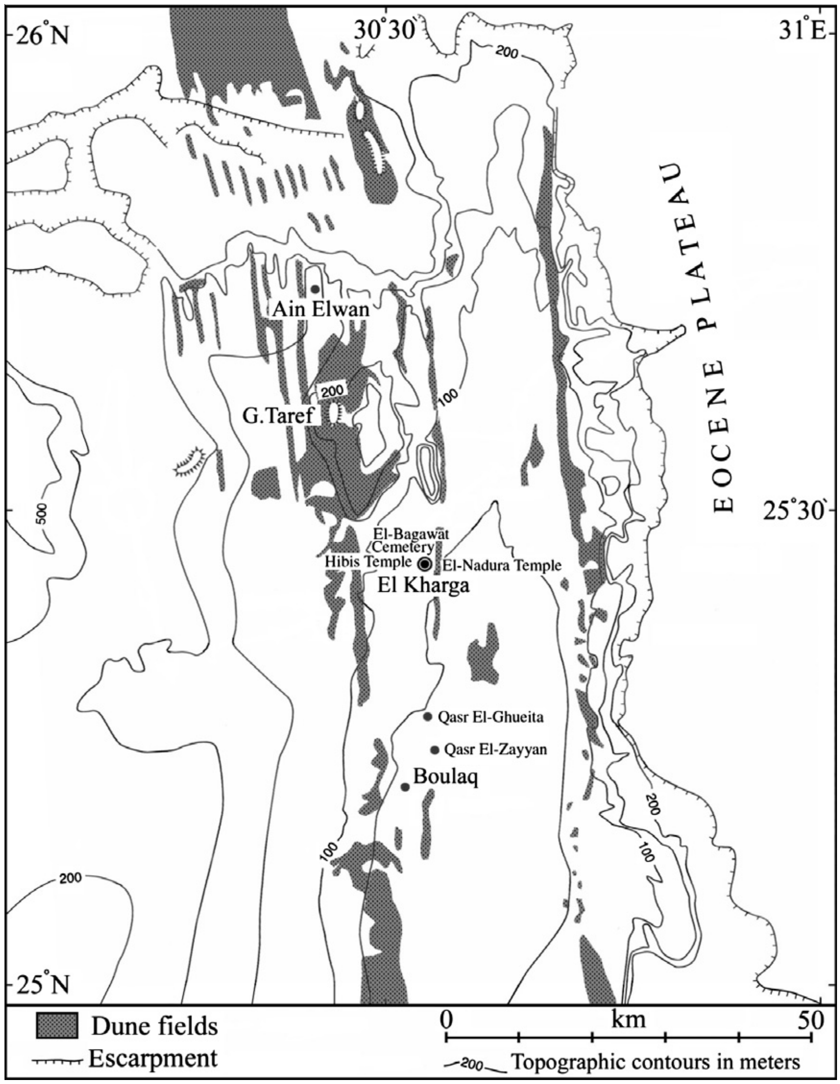

Fig. 4. Map showing the dune-fields distribution at Kharga Oasis (modified after Stokes et al., 1999).

asphaltic materials for fixation (Hilmy et al., 1980). The rate of movement of the dune depends mainly on the dune size and the amount of moisture in the surroundings (Embabi, 1986). These dune belts continue through the Kharga depression where several groups of barchan belts are formed and extend southward far beyond the depression.

The structural elements of Kharga area are the result of typical stable shelf tectonics. Faults and, to a lesser extent, large-scale gentle folds are observed on the surface indicating differential block movements in the underlying basement (Fig. 5). The resultant deformations in the overlying sedimentary cover are governed by its lithology and thickness. Structural analyses revealed that nearly N–S trending normal faults are dominant in the northern Kharga area (north of latitude 25°N). These faults extend over the depression and along the eastern and northern scarps as well. The most prominent faults encountered in this sector are Quarn Ginah-Boulaq faults, Taref-Teir faults, Umm El-Ghanayim-Ghanima faults and the step faults along the northern Scarp. The extensions of these faults range from 4 to more than 30 km, following different trends that may slightly deviate from the N–S trend to the NNW or to the NNE directions. The vertical displacements of these normal faults range from 5 to 225 m with the down-thrown blocks to either east or west (Ghobrial, 1967). On the other hand, the E–W trending normal faults are the most common set of faults that affect the south Kharga area (south of latitude 25°N). In this area, faulting is the dominant structural feature with greater density and persistence due to the relatively thin sedimentary cover. A group of parallel faults extending in a nearly E–W direction for distances of more than 50 km divides the southern Kharga area into parallel blocks of variable width.

Several domal or basinal structures with steeply inclined flanks were developed in association with this group of faults. The domal structure of Quarn Ginah is topographically expressed as conspicuous hillocks located to the north of El-Ghueita Temple, which could have been initiated in pre-Cretaceous times as indicated by the fracture system within its sandstone layers belonging to the Taref Formation (EGCO, 2005).

4. Environmental geology of the monumental sites

Basically, the natural processes of both rapid and slow geological evolution continue to impact the investigated area. Such natural processes are not completely under human control to any significant extent. However, the most important processes are, among others, (i) climatic variations responsible for earth-surface processes (e.g. active winds, floods, etc.); (ii) physical and chemical properties of the exposed bedrocks; (iii) earthquakes; (iv) landslides and avalanches; (v) volcanic explosions.

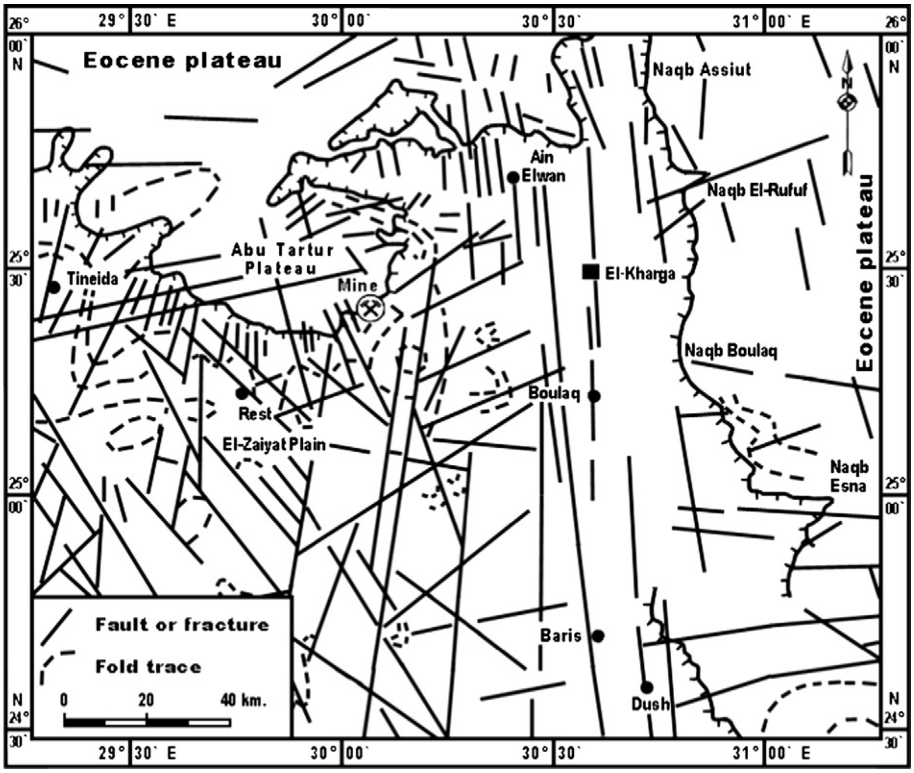

Fig. 5. Structural lineaments map of the Kharga Oasis (after El-Shazly et al., 1980).

Climatic variations and their consequent earth-surface processes represent the most prominent factor delineating the environmental impact on the study area in the present hyperarid South Western Desert of Egypt in the Eastern Sahara. Geological, archaeological and paleoclimatic reconstructions indicate that the climate of the Eastern Sahara during the early to mid-Holocene (9300–4500 years BP) was much wetter than today (Haynes, 1982; Szabo et al., 1995; Yu and Harrison, 1996; Claussen and Gayler, 1997; El-Baz et al., 2000). This wet phase was characterized by rapid onset with the formation of a mosaic of freshwater lakes and swamps leading to groundwater recharge of the Nubian aquifer (Pachur and Hoelzmann, 2000). In contrast, its termination shows depletion of the aquifer during several centuries when exploitation of the non-renewable groundwater resources represented the adaptation strategy of the Neolithic population. In addition, increasing aridity became pronounced about 3000 years ago (Besler, 2000), which was expressed in sand dune reactivation and migration further south in the Western Desert of Egypt. Then, extensive use of groundwater for domestic and irrigation purposes from natural springs and deep wells during successive periods led to the present-day lowering in the static levels to tens of meters below the depression floor.

The impact of groundwater on the study area is pronounced. Natural groundwater springs are structurally controlled and restricted to the faulted areas located in the middle (lowest) parts of the depression. This suggests that the Nubian aquifer in southwestern Egypt is a fracture dominated rock aquifer rather than an ordinary horizontally stratified aquifer (Robinson, 2002). Also, along these faulted areas, the Nubia Sandstone blocks are dislocated, emerging upward and forming raised hillocks. The archaeological sites are restricted to these hillocks due to their rocky terrain suitable for the foundation of large structures. From another point of view, dense cultivation surrounding the studied monumental sites, especially Hibis Temple, could threaten the stability of the foundations of the monuments through lateral seepage of saline drainage waters. Applying flood irrigation techniques and the absence of adequate drainage systems are most likely responsible for such harmful effects.

From the field survey, it is clear that the bedrock lithology plays an important role in the extent of damage. The geologic maps for the studied areas (Figs. 6 and 7) illustrate that the floor of the Kharga depression is mostly covered by purple and green variegated shales that alternate in places with some sandstone and siltstone layers belonging to the Nubia Formation. The sandstone beds are light brown, slightly hard, highly cross-bedded and fractured. They are partly ferruginated and silicified, especially along some bedding planes. These rocks sometimes protrude in the form of low to moderate elevation hills scattered on the central part of the depression floor, over which successive cultural sites comprising temples, desert garrisons, etc., were established (Figs. 8 and 9). Nevertheless, some important monumental sites such as Hibis Temple were constructed directly on the vast peneplained variegated shale floor of the depression. A test hole in the temple area indicated that the underneath bedrock is composed of thick shale beds, reaching more than 14 m in thickness. These varicolored shale and clay beds occasionally contain gypsum in the form of patches, veins and lenticular pockets (Fig. 3b and c). Consequently these beds are highly fractured and crushed. On the other hand, their clay mineralogy is very important as a geotechnical factor. X-ray diffraction of the samples obtained from this 14 m test hole representing the bedrock under Hibis Temple reveals the presence of an appreciable amount of smectite, kaolinite and illite clay minerals, in decreasing order of abundance. These clay mineral admixtures with the principal component of quartz grains encourage swelling potential leading to soil creeping and foundation instability in the site of Hibis Temple.

Sand dune belts cover approximately 20% of the depression floor, and they mostly bound the studied monumental sites (Figs. 4, 6 and 7). These dunes are active sources for wind-blown sediments that contain erosive quartz grains which abrades the various com-

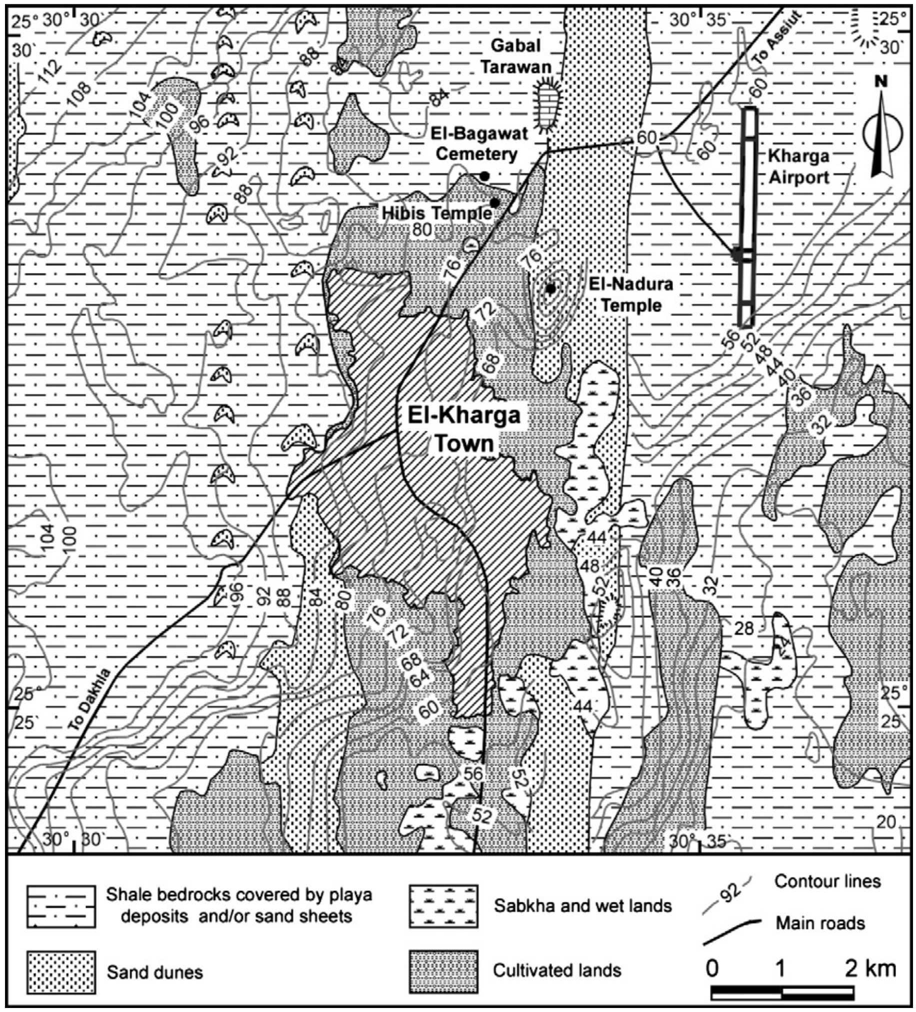

Fig. 6. Map showing surface geology of the northerly located monumental sites, Kharga Oasis (after EGCO, 2005).

ponents of the monuments. Sand dunes form a real hazard to most of the monumental sites. These dunes are moving fast (average rate of downwind migration is 9.3 m/year; Stokes et al., 1999) and partly accumulate nearby some monumental sites and completely destroy some relatively recent villages and some cultivated lands. These dunes also represent a near source for feeding the sandy-wind storms which make wind erosion via sand blasting very destructive in these sites.

However, the surface geological processes that impact the monumental sites can be summarized as follows:

Hibis Temple site is founded on bedrock consisting of shale beds reaching more than 14 m in depth. This shale is considered as highly expandable bedrock, weak in its bearing capacity, as its clay content (mainly smectite) experiences swelling upon wetting from the shallow groundwater underneath. The monumental site is surrounded by dense cultivation, which represents another threat to the stability of the temple foundation. The source of water seepage beneath is partly from agricultural return flow, which affects the shallow groundwater table. In addition, the temple complex is located on a low-land bounded with sand dune belts in the eastern and western sides with their sand-blasting hazards.

El-Nadura and El-Ghueita temples are hilltop fortress temples, located on hillocks raised above the surrounding flat depression floor. The same landscape is encountered at El-Bagawat Cemetery site, which was constructed on a flat-topped hillock. These hillocks are composed of alternating sandstone, siltstone and shale beds representing the lower part of the Variegated Shale unit of the Nubia Formation. On the other hand, El-Zayyan Temple is located on slightly raised sandstone ground surrounded by cultivated lands. The groundwater table is seemingly less hazardous relative to Hibis Temple monumental site as shown in the sketches (Figs. 8 and 9) and unlikely to undergo hazardous effects in this case. However, these temples could be threatened by slope instability of the site-surrounding cliffs which could enhance differential settlement of its foundations.

5. Petrographical investigation

The lithological characteristics of the different types of building materials (building stones, mortar, plaster, etc.) are believed to represent potential threats to the archaeological sites in Kharga Oasis. Thin sections representing these building materials were prepared and examined using a polarizing microscope. The results reveal that building stones are mainly composed of subrounded to well-rounded, well-sorted, medium to coarse-grained quartz (Fig. 10a–c). These grains are almost monocrystalline quartz and show grain-supported fabric. These sandstones are considered quartz arenite according to Tucker (1981). They are the most compositionally mature type of sandstones, being composed entirely of quartz grains, with rare feldspars and rock fragments. These grains are cemented by either quartz overgrowths (silica cement) or iron

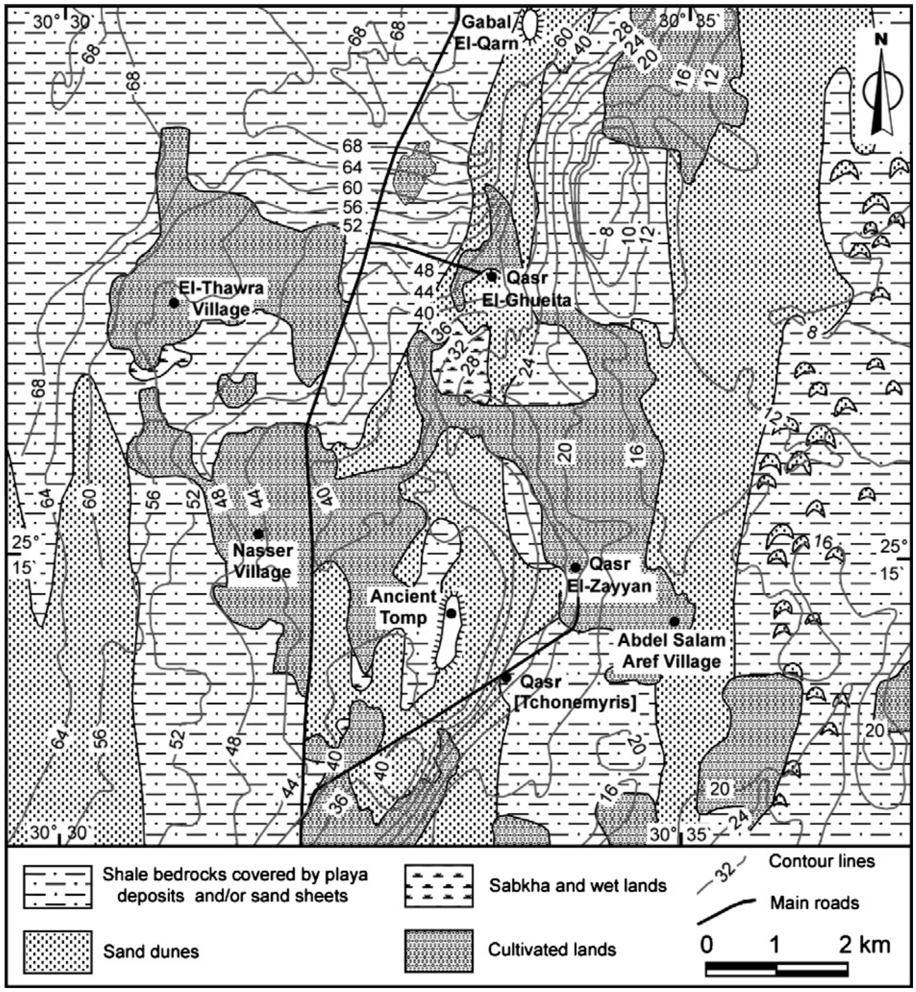

Fig. 7. Map showing surface geology of the southerly located monumental sites, Kharga Oasis (after EGCO, 2005).

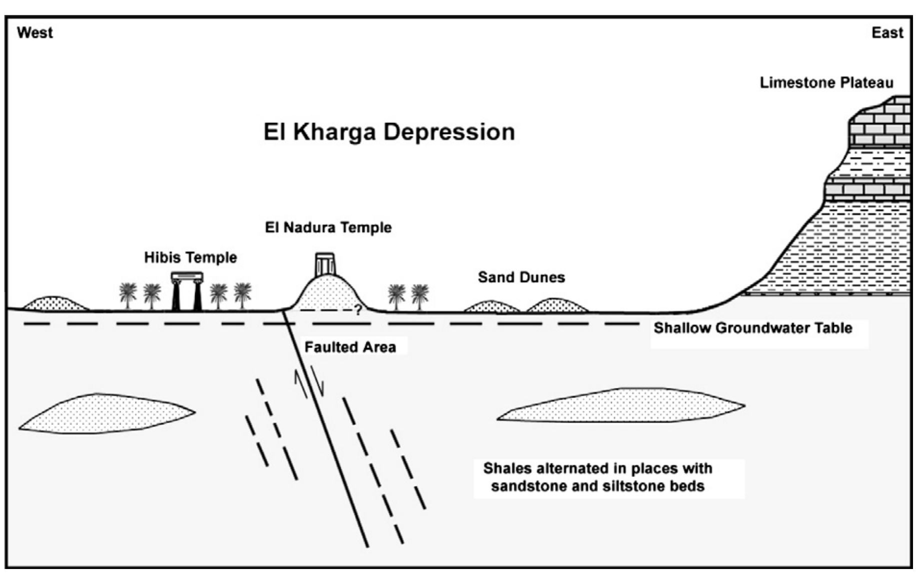

Fig. 8. Sketch showing geologic and physiographic landscape characteristics of the area surrounding Hibis and El-Nadura temples at Kharga Oasis (not to scale).

oxides that frequently fill the secondary porosity. The observed mechanical compaction resulted in re-orientation and re-packing of detrital grains appearing long and concavo-convex grain contacts, and pore-filling cementation with iron oxides are considered early diagenetic features in the original sandstone beds from which the building stone blocks were cut. This well-developed cementa-

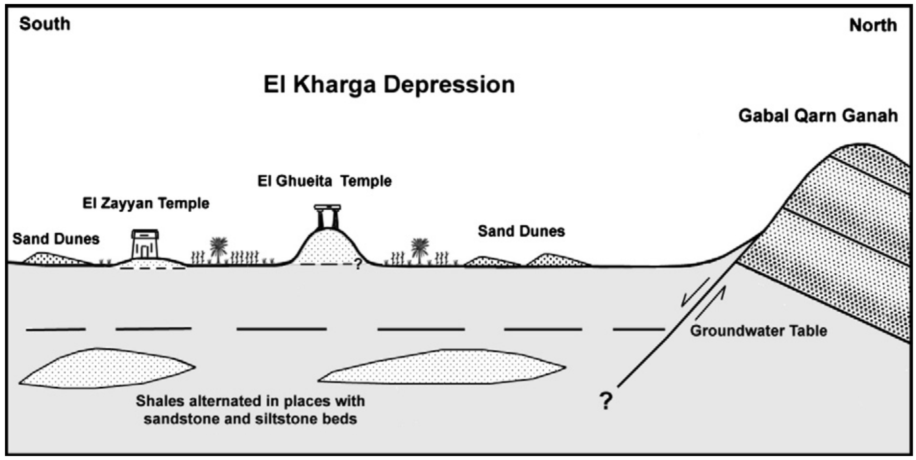

Fig. 9. Sketch showing geologic and physiographic landscape characteristics of the area surrounding El-Ghueita and El-Zayyan temples at Kharga Oasis (not to scale).

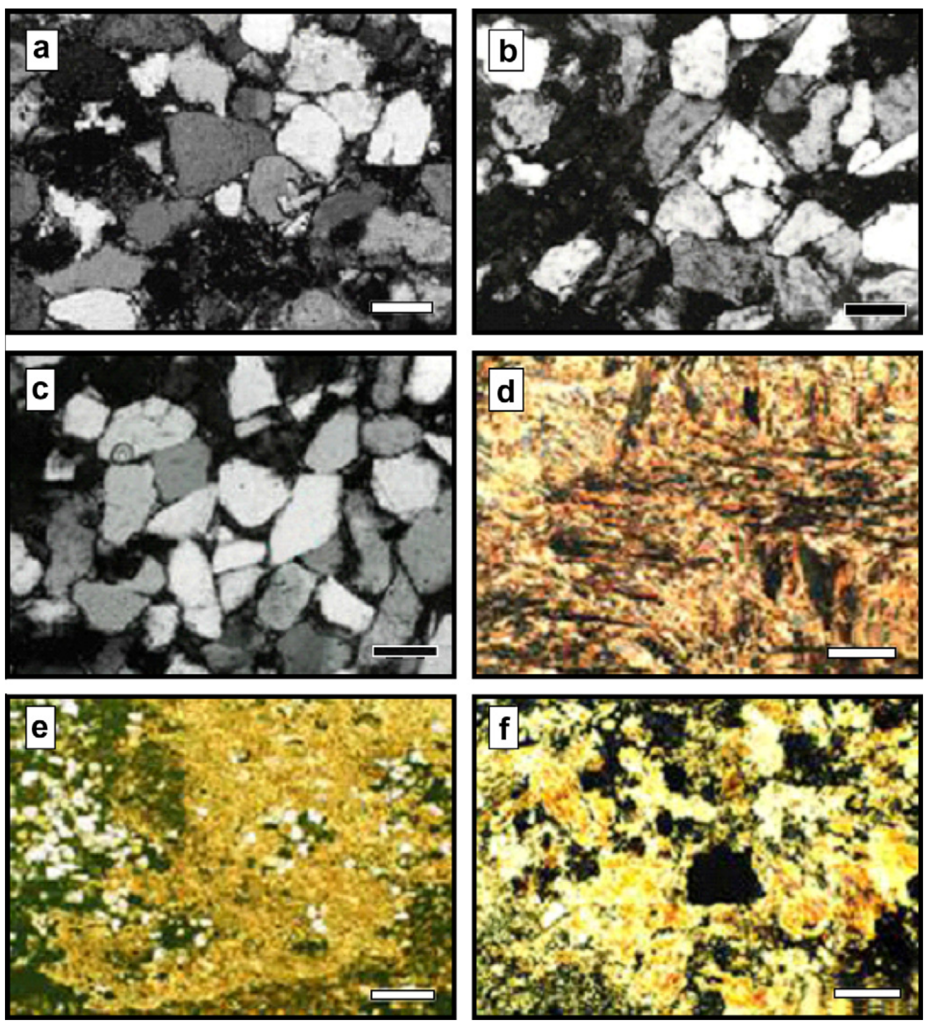

Fig. 10. Photomicrographs of building materials showing: (a–c) building stones composed entirely of quartz grains with frequent silica overgrowths, long and concavo-convex grain contacts by compaction, besides iron oxide cement and cavity filling, (d) plaster material composed of anhydrite showing sub-parallel microcracks, and (e and f) calcareous mortar material with partly to completely dissolved quartz grains floating in calcareous cement. All micrographs are under crossed polars, bar scale equals 400 μm.

tion of the framework quartz grains gives the stones its highly indurated character that is responsible for its good state of preservation over time.

Both mortar and plaster (Fig. 10d–f) are necessary building materials. Any change in their properties with time could lead to damages on the monumental buildings. The studied plaster materials collected from the sites are mainly composed of anhydrite (Fig. 10d) associated with different proportions of quartz with different grain size, sometimes reaching up to the granule size of 2–4 mm. These plaster materials were used for the decoration of the interior walls and ceilings. Clear signs of etching and corrosion with different grades were recognized. Another type of muddy plaster material was recorded in El-Bagawat Cemetery. This argillaceous plaster is composed of varying-sized quartz grains, and to a lesser extent, broken fossils tightly compacted with muddy material. No signs of etching between the mud cement and the framework quartz grains were observed.

6. Environmental radioactivity assessment

Radioelement concentrations were recorded using the gamma-ray spectrometer in the studied monumental sites. Potassium in percent (K%), equivalent uranium (eU in ppm) and equivalent thorium (eTh in ppm) were determined after background and stripping corrections. The average values at each of the studied sites were converted to environmental units expressed as annual effective dose equivalent values of gamma radiation in milli-sievert per year (mSv/year) according to the relationships provided by the International Atomic Energy Agency (IAEA, 1990).

Radiometrically, the floor of Kharga Oasis shows variable values, depending on the bedrock types and their content of the major natural radioelements (K, U and Th). At each monumental site, more than 25 sporadic measurements covering the exposed bedrocks, soils, building materials, etc., were carried out over 100 s count time. This ground gamma spectrometric survey revealed that the annual effective dose equivalent values are generally very low, averaging 0.20, 0.13, 0.09 and 0.07 mSv/year for the monumental sites at Hibis, El-Nadura, El-Ghueita and El-Zayyan, respectively. The slightly higher value at the Hibis site is related to the exposed shale bedrocks.

The IAEA (1990) states that for most rocks and soils, the contribution of natural terrestrial radioactivity to the annual effective dose equivalent is less than 0.5 mSv/year, but levels of up to 2 mSv/year are frequent. However, the permissible exposure effective dose for an individual person in the general public is below 1 mSv/year, and the occupation effective dose for nuclear workers is limited to 20 mSv/year (IAEA, 1996). Accordingly, the investigated sites represent safe areas as the natural environmental radiation effective dose equivalent values do not exceed the lower limit of the permissible safe radiation dose. This environmental radioactivity monitoring of monumental sites is very important for residents and visitors, and it is of critical concern to environmental protection agencies.

7. Potential hazards and deterioration features

Several potential threats are believed to impact the archaeological sites in Kharga Oasis. These threats include soil defects, groundwater impacts, sand dunes and wind erosion, biological and microbiological effects and man-made impacts represented by inadequate restoration, and in some cases, through graffiti. These factors damage the color of the wall paintings, walls and can create column fracturing.

7.1. Groundwater and soil hazards

These are clear in Hibis temple where it suffers from foundation failure and the presence of cracks in different parts of the temple. Continuous upward movement of groundwater levels has been noticed in the study area as evident from the presence of sabkha and ponded water (Fig. 11). The upward movement of water is mainly due to groundwater input from a leaking water supply and drainage systems. Fig. 11 shows water ponds and dense cultivation near Hibis Temple, while Fig. 12 shows fracturing in its outer wall and columns. Also fractures and shear were seen in the sandstone blocks in El-Ghueita Temple, but these fractures are not related to the groundwater effect (Fig. 13).

Another natural process that contributes adverse impacts on the structure of the monuments is capillary water flow. It infiltrates through walls and columns, and when this water evaporates, salt crystals are left noticeably on the outer surface of the building elements. The force of salt crystallization exerts pressure and causes cracking and disintegration of the wall materials. The crystallization of soluble salts on the surface is due to the low rate of ventilation, which makes an evaporation rate lower than the rate of replenishment of water by capillary migration from inside the wall. The salt crystals are formed mainly outside the pores and consequently the disruptive effect is smaller. When efflorescence takes place, the soluble salts are brought to the surface during the wetting phase, and when evaporation from the surface takes place during the drying phase, salt crystals form on the surface. Very often, foundations move because of loads applied upon them, bed subsidence, soil erosion caused by flowing water, changes in groundwater level or swelling/shrinkage of clay soils. The above factors are believed to be existing in Hibis Temple site (Fig. 11a).

7.2. The sand dunes hazard

It represents the most dangerous hazard on the monumental sites in the Kharga Oasis area. Sand dunes are well developed along the Kharga depression. Dune belts are oriented parallel to the long

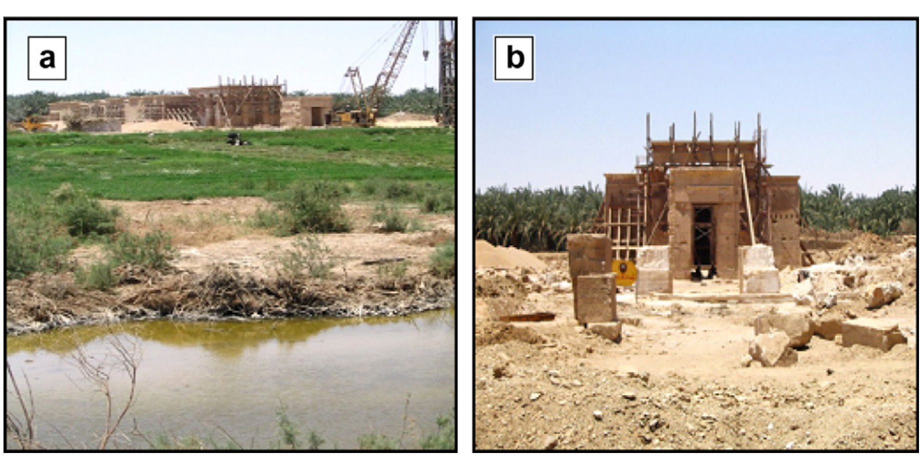

Fig. 11. Field photographs showing water pond (a) and agricultural fields (b) nearby Hibis Temple.

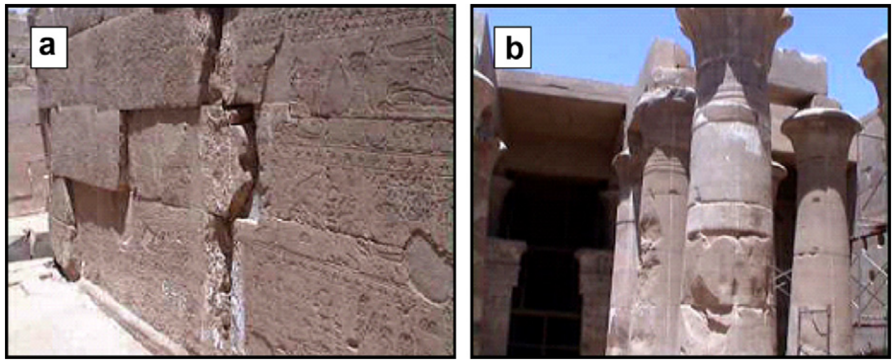

Fig. 12. Block dislocation and warping of outer wall (a) and severe deterioration in columns (b), Hibis Temple.

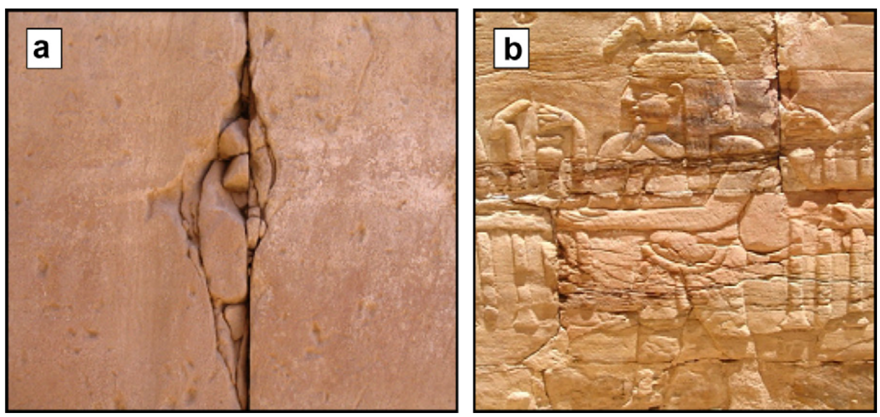

Fig. 13. Sandstone blocks showing lenticular fracture (a) and partial destroy of relief by minor fractures (b), El-Ghueita Temple.

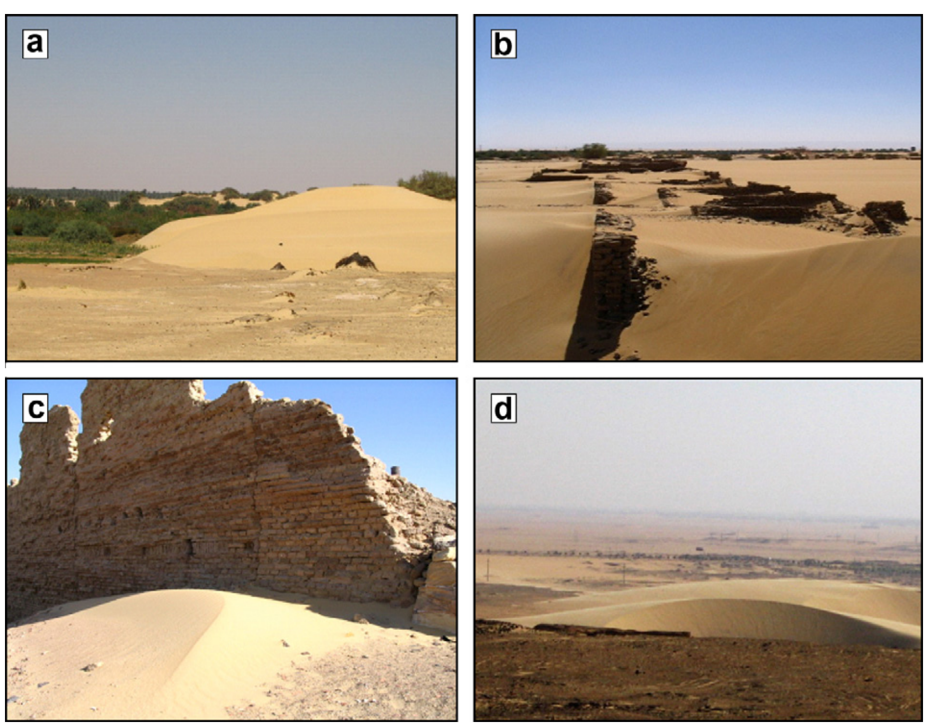

Fig. 14. Field photographs showing: (a) sand dune overwhelming cultivated lands at Ganah village, (b) sand dunes completely destroyed a village located to the north of El Ghaueita Temple, (c) sand accumulation below the northern walls of El-Nadura Temple; notice the severe sand blasting of mud bricks, and (d) cluster of sand dunes moving towards El-Nadura Temple site, Kharga Oasis.

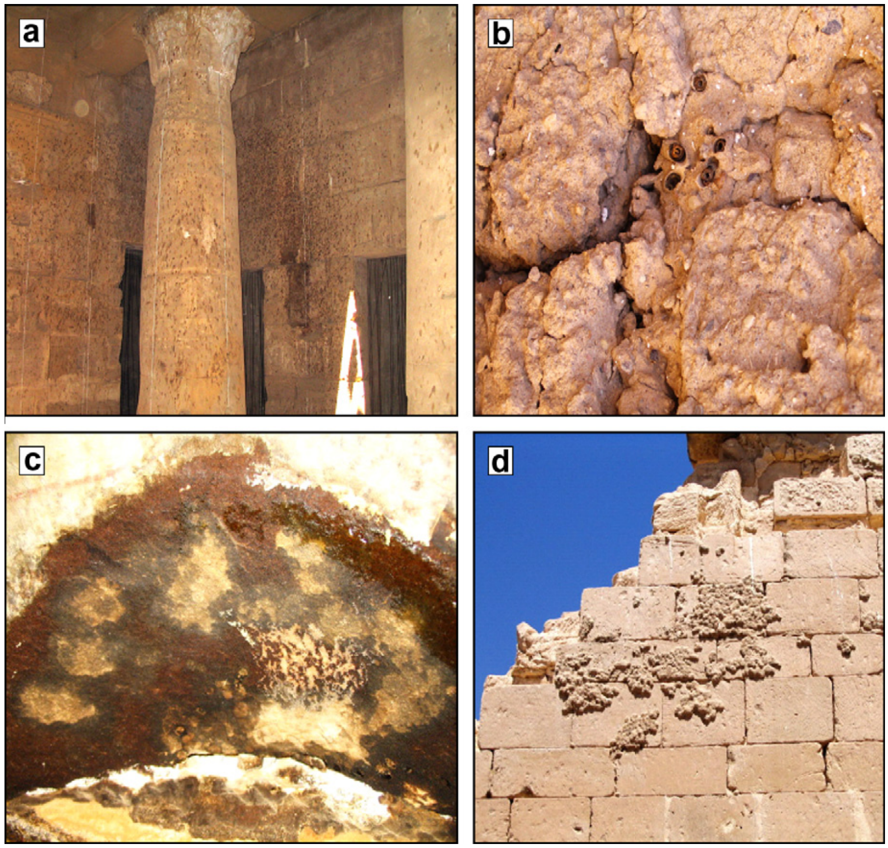

Fig. 15. Photographs showing bio-deterioration features in Hibis Temple (a), in El-Bagawat Cemetery (b), in El-Ghueita Temple (c), and in El-Zayyan Temple (d), Kharga Oasis.

axis of the depression coinciding with the direction of the prevailing northerly winds. The spatial distribution of the Kharga sand dunes indicates that they can be grouped into three belts. The western belt is a continuous belt of simple barchan dunes and compound barchanoid ridges running from the northern scarp to the south of the Abu Bayan area by about 40 km, where it becomes wider and then dispersed into the open desert. The middle belt of barchans is smaller but of great importance due to its hazardous impact on monumental sites, roads and agricultural fields in the cluster of villages arranged longitudinally in the middle part of the depression floor. The eastern belt runs parallel to the north–south oriented eastern scarp. This belt is characterized by barchans, shadow dunes and sand sheets accumulated at favorable sites either on the pediment slopes or in the course of the descending valleys where they sometimes cause blockage.

It is evident from this environmental geologic study that the sand dunes form a serious hazard to the monumental sites and some of the development projects in the Kharga Oasis depression (Fig. 14a and b). It is evident also that the movement rate of these dunes is 30–40 m/year (Issawi and El-Hinnawi, 1982). The hazard of the moving sands from the huge sand dune belt to the north of El-Nadura Temple is very clear. In this site some sands derived from the nearby dune belt started to accumulate around the temple (Fig. 14c and d).

7.3. Biological hazards

During the field investigation, it was evident that biological activities manifest a remarkable hazard on the monuments in Kharga Oasis sites. Their damage effects were very clear on all the studied monumental sites. Small birds can damage soft stone with their bills. The damage caused by their bills might not be very conspicuous on broad stretches of ashlars, but on carved features in soft stone it can become a matter for concern.

Additional damage occurred as a result of roosting and nesting of birds on masonry. Deterioration is caused mainly by the accumulation of their excretions and nesting materials. These can form compost, which breaks down as a result of bacterial action and releases acids which alter limestone and calcareous sandstone. The compost also contains salts, which might cause crystallization damage to any susceptible type of stone. Mason bees impact the stonework of the investigated sites. The affected stones are mainly loosely bonded possibly argillaceous sandstones. Fig. 15 depicts the bio-deterioration hazards in the most of the temples in Kharga Oasis area.

Humidity, temperature, sunlight and water content conditions seem to be favorable for biodegradation as evidenced by the presence of algae, bat blood and bird excretions. Organic acids such as oxalic and citric acids can be produced biologically from the observed biological components. These acids can dissolve calcium carbonate, which is the main constituent of limestone. However, it has yet to be proved what proportion of the total decay of limestone is attributable to biological activities versus other hazards at the sites.

8. Conclusion and recommendations

The action and interaction between the environmental geology and the monumental sites in Kharga Oasis are clear. Sand dunes form a serious hazard to most of the reported monumental sites. These dunes are moving fast and accumulate nearby the monumental sites and have partially destroyed recent villages and some cultivated lands. These dunes represent a feed source for sandy-wind storms which make wind erosions very effective at these sites. The groundwater effect is rather clear at the site of Hibis Temple due to its presence in a relatively low topographic level in Kharga Oasis depression. The source of the groundwater is mainly from the irrigation water used for the densely cultivated nearby areas. Another important hazard factor is the biological action of birds and other micro-organisms. Moreover, the man-made deterioration factor is not uncommon. From the radioactivity perspective, the investigated sites represent safe areas because the natural environmental radiation effective dose values do not exceed the lower limit of the permissible safe radiation dose.

The following points are recommended for the preservation of these cultural heritage sites: (1) the groundwater situation in the site of Hibis Temple should be monitored and must be kept in a suitable and safe level. This is important because the groundwater can impact the foundation bed. The water source should be also be blocked by constructing some isolating barriers based on a thorough study for the underground water and seepage conditions. De-watering of the soil under the temple is recommended, meanwhile grouting is another alternative proposal, (2) performing an additional detailed study for sand dunes around all monumental sites in Kharga Oasis. This study should include the wind dynamics, rates of dune movements in each direction, the factors controlling dune movements and their accumulations in such an arid environment and (3) applying adequate techniques to reduce the biological action on all the monumental sites. That is because the biologic effect is very dangerous, especially on the reliefs of the archaeological sites.

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