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Composition and diagenesis of ancient Shali city buildings of evaporite stones (kerchief), Siwa Oasis, Egypt

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ABSTRACT

Shali is an ancient fortress, built in the XII–XX century in Siwa, Northwest Egypt. It is built on two Middle Miocene limestone and marl hills, between the wadi plain. The architecture of the fortress buildings is composed of local materials derived from the Miocene, Quaternary, and recent salt lake deposits. The framework blocks of the city are mainly composed of salt (Kerchief), limestone, and bentonite, wood particles, dry date seeds, and bones derived from ancient tombs. In this study, the modification and mineral phases that developed during the diagenetic alteration and cementation of the salt and clay mortars with different framework in the walls of the ancient houses and settlements will be followed and interpreted. Diagenesis included transportation of salt materials from the nearby Fetnas Lake and mixing with some sand and clays as mortar pressed into the voids between the frameworks (Kerchief blocks). This resulted in dehydration, gypsum crystallization, and halite cementation. The continuous crystallization through the epitaxial growth of halite in both cement and framework blocks results in strong adhesion and binding of the framework. At the end of the process the kerchief blocks and the cement will be completely homogenous to a point that they apparently no longer be distinguished.

1. Introduction

Salt houses have been documented in a number of ancient cities all over the world. For example, one of the well-known recent salt house hotels is found in Salar de Ayuni, Colchani, Bolivia. Taghaza is an abandoned salt-mining center located in a salt pan in the desert region of northern Mali. It was an important source of rock salt for West Africa up to the end of the 17th century. At Dallol volcano located in the Danakil Depression in NE Ethiopia, ruins of potash houses are found. The volcano rises 50–60 m above the surrounding salt plains, nested on top of an almost 1000 m thick layer of evaporites.

Siwa oasis is located in northwest Egypt near the Libyan border, 300 km southwest of Mersa Matruh Governorate, covering an area about 7500 km^2 (Fig. 1A). The climate is extremely arid all the year except from January to June where the precipitation reaches 2 mm, and in July it reaches 9 mm. Siwa is dominated by high summer temperatures (maximum 37.7 °C in July and August and the evaporation rate varies from July to December between 16.5 and 5.5 mm/day. It is characterized by constant climatic conditions throughout the year and has monthly average temperature of 35 °C, humidity of 58% and 300 average sunshine hours per month (Gindy and El Askary, 1969; World Climate Charts, 2010).

Geomorphologically, Siwa comprises closed flat depressions bordered to north by a limestone plateau with a steep escarpment running E–W and to the south by sand dune areas (Great Sand Sea). Inland saline lakes (−20 m), rock inselbergs and cultivated land are the main features within the depressions (Fig. 1B). The relief of the cultivated land ranges between −6 and −17 m. Naturally flowing springs are confined to the floor of the depression. The spring waters are used to irrigate the palm and olive plantations, and drain into the salt lakes. In recent years, more deep wells have been drilled causing a rise of the water table close to the surface level (Hammad et al., 2000). This causes the formation of widespread salt efflorescence on the surface, walls of buildings and rock outcrops. The Siwa region is thought to be a tectonically induced depression formed through successive tectonic events, and shaped finally by topographic processes (Masoud and Koike, 2006).

2. Shali fortress

Shali is an ancient fortress, built between twelfth and twentieth century in Siwa, on two Miocene hills separated by a wadi plain

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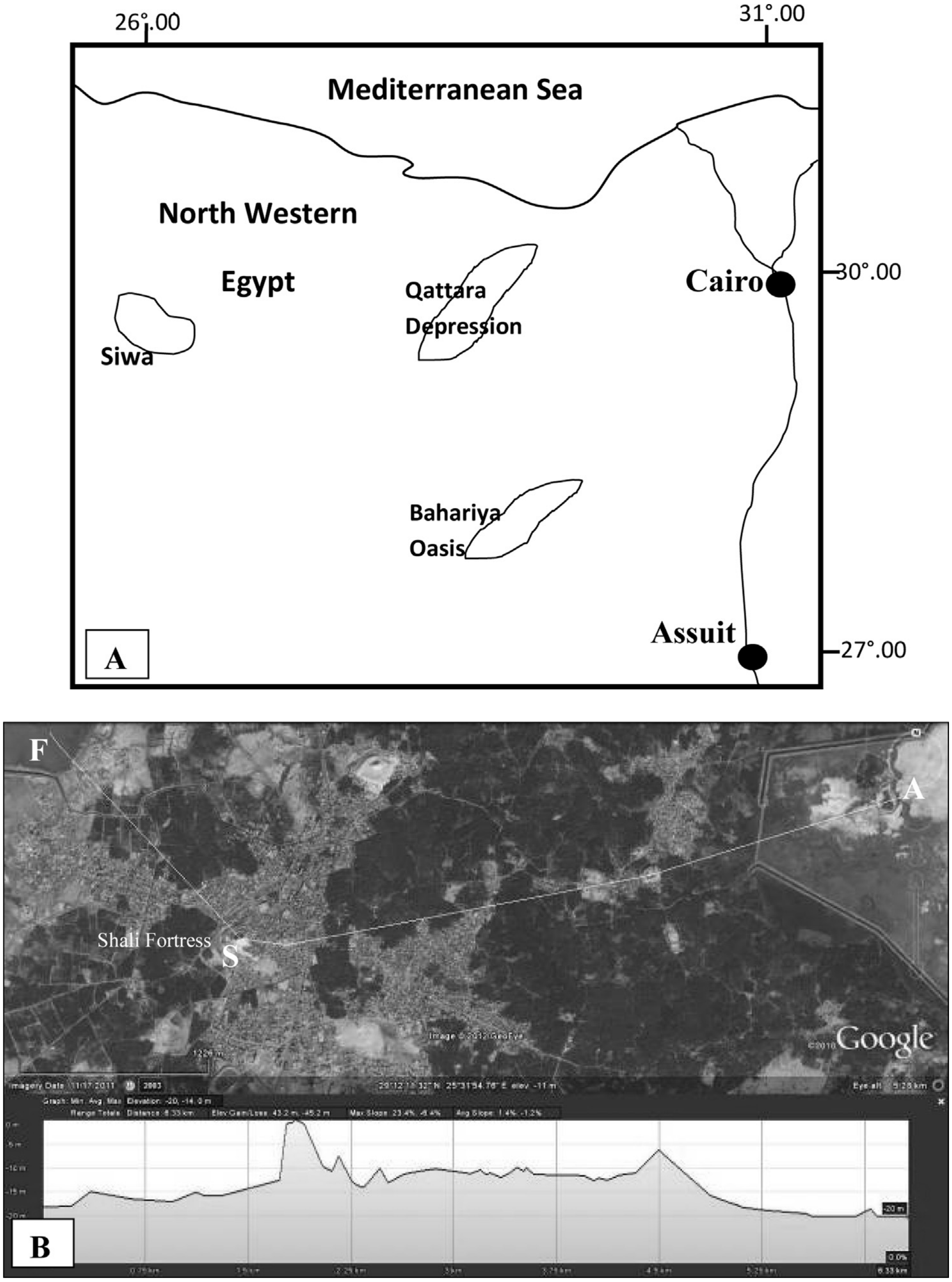

Fig. 1. A) Location map of the study area. B) Satellite image of Siwa city clear the position of Shali fortress (S) in relation to Lake Aghormi (A) and Lake Fetnas (F). The cross section FSA show the maximum elevation of Shali Fortress is 0 m while the lowest point is −20 m (the data is adopted from Google earth).

(Fig. 2A, B). It resembles an ancient castle whose rough ramparts tower above the forests of waving palm trees, and the rich green gardens. The houses are built of mud, mixed with salt, with occasional large blocks of stone from the temples let into the walls. The vast thickness of the walls makes the houses cool in the high temperature summer period, and warm in winter when cold winds sweep down from the high desert plateau. The windows are very low. The ceilings are made of palm trunks covered with rushes and a layer of mud. The ends of the trunks are long, projecting outside the walls, and serve as dowels on which to hang bundles of bones to avert the "Evil Eye" (Fig. 2C, Belgrave, 1923). Palm trunks constitute the supporting structure of the floors at different levels and by other wood insertions (some olive wood) to form connections. One architectural peculiarity is that the builders worked without a line, gradually adding to the wall, sitting across the part which they have completed, so few of the walls are straight (Belgrave, 1923; Cassandra, 2000). Another architectural peculiarity is that, owing to the need of building walls thicker at the bottom (about 2 m thick) than at the top (30–60 cm thick) most of the houses, especially the minarets of the mosques, become narrower towards the top (Fig. 2D, E). The houses are built one above the other against the face of the rock (Fig. 2D), and the external walls form one distinct line of battlements, penetrated by little groups of square windows, encompassing the town, and rising sheer above the ground, in some places to a height of almost 60 m (Belgrave, 1923). Today, the heights of the buildings do not exceed 35 m. As the inhabitants

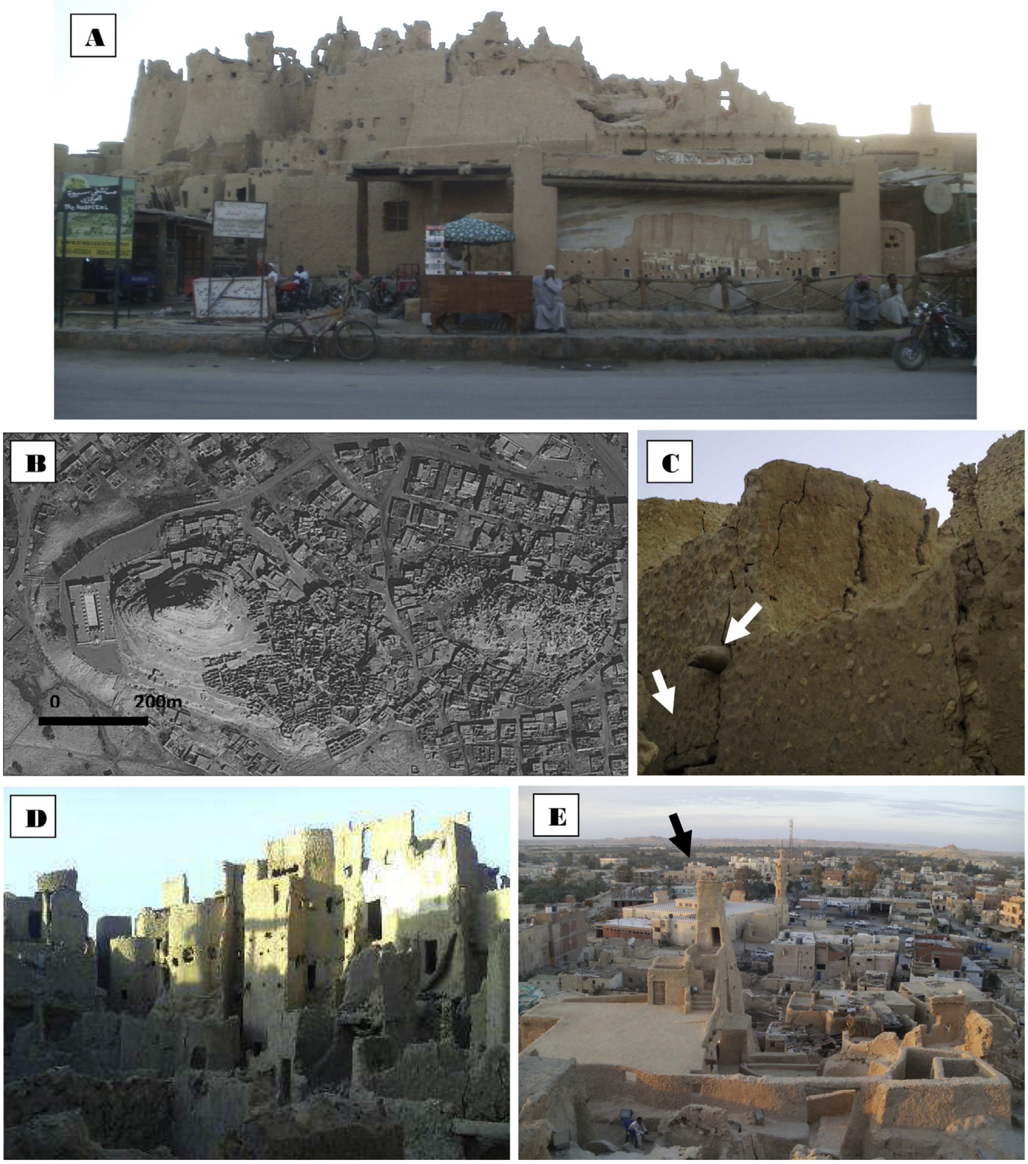

Fig. 2. A) Panoramic view of Shali fortress, the lower part of the photo showing the sketch photo of Shali in the year 1900, B) Satellite image of ancient Shali City, Siwa area, Egypt adopted from Google map, C) Palm trunks (arrows) supporting the floor and projecting outside the wall, D) External architecture of Shali buildings in which houses are built one above the other against the face of the rock. E) The main mosque of Shali with a narrow minaret (arrow).

increased, more houses were built on the top of the old ones, and the town, instead of spreading, began to rise upwards into the air, house upon house, street upon street, and quarter upon quarter. The houses were connected by steep, twisting, dark and narrow passages with little low doors of split palm logs opening into them from the tenements above. The mud of which the walls were built gradually hardened and became almost of the consistency of the original rock.

3. Geologic setting

Geologically, Siwa is subdivided into three main Middle Miocene lithologic units which are extensively exposed: a lower older Siwa Oasis Member, forming the floor of the depression and consisting mainly of shales and marls; a middle Siwa Escarpment Member, forming the slopes of the detached hills; and an upper El-Diffa Plateau Member, that occupies the upper surface of the plateau (Gindy and El-Askary, 1969; Mueller et al., 2002). The escarpment and the plateau consist principally of chalky limestone, limestone, and dolomitic limestone.

The oasis extends east–west along a depression 20 m below sea level and bordered to the north and west by the rocky hills of the El Diffa Plateau, and to the south and east by the dunes of the Great Sand Sea. The depression has six salty lakes: Maraqi, Siwa, Zaiton, Abu Sherouf, Aghormi and Maraqui and many natural artesian springs used for irrigation which fed into the lakes. Masoud and Koike (2006) detected four major vertical to near vertical fracture zones trending NW–SE, WNW–ESE, NNE–SSW, and NE–SW which comprise two nearly perpendicular conjugate sets of faults. The conjugate sets of faults are found to intersect in Siwa Lake, providing a zone of high conductivity for groundwater.

4. Materials and methods

The sampling sites were selected after a careful field examination in order to have representative samples from the dump of the

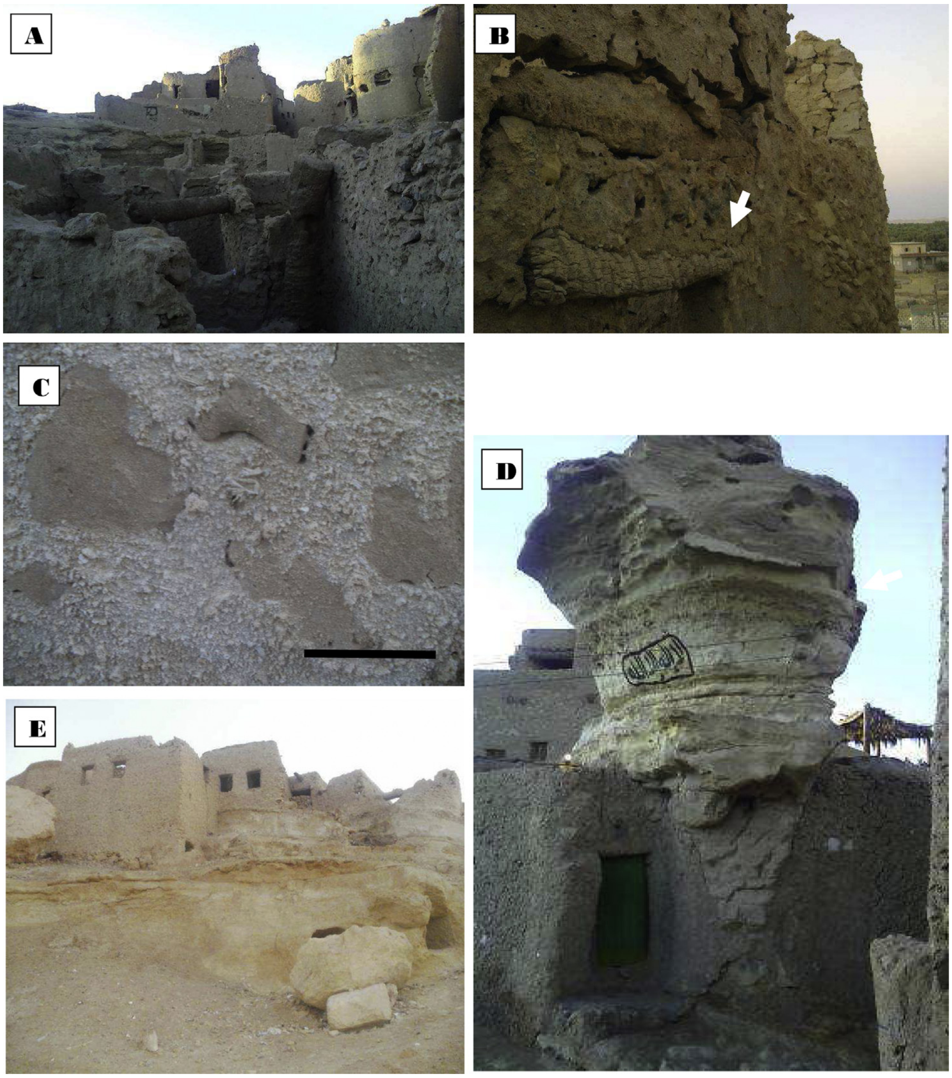

Fig. 3. A and B) The framework components of the walls which made entirely of kerchief and Miocene limestone fragments with additives of pottery, shale fragments, bones and date seeds C) Close up of the Kerchief blocks of irregular shape (Scale = 10 cm) D) New restored house beneath an atoll remnant of limestone of Middle Miocene, E) the houses are built following bedding planes of the Miocene rocks.

destroyed houses as well as broken walls. The samples cover the main composition of the city as well as the different weathering materials. A group of framework components derived from the Miocene basement and substrate rocks were carefully sampled and investigated. The investigation included petrographic examinations, XRD, and Scanning electron microscopy (SEM) analysis. The mineralogy of investigated samples was determined by means of a Philips Powder Diffractometer Model PW 1170 employing CoKα radiation on randomly oriented specimens. The sample was scanned over the 2θ degree range 0–40 2θ. Samples for SEM study were critical-point dried, gold-sputtered, and studied under the SEM Jeol JSM 35 CF, Tokyo.

5. Results and discussion

5.1. Framework components

The fortress buildings are composed of local materials. The framework components of Shali fortress vary in size and made mainly of slat blocks (kerchief), limestone and shale fragments (ancient Miocene), wood particles, dry date and olive seeds, and bones derived from ancient tombs (Fig. 3A–C). The kerchief is made of an unusual material of NaCl salt crystals with impurities of sand and clay. Kerchief blocks of irregular shape were directly extracted from the salt crust that surrounds the salty lake. Salt blocks were used without any regularization or rectification because of the tendency of the salt to break (Fig. 3C). The kerchief are cut in smaller blocks and used in the buildings with a mud mortar very rich in halite salt crystals. During drying, a strong connection is established between the salt blocks and the mortar due to the crystallization of NaCl inside the mortar itself, giving rise to a durable and more homogeneous rock. Field investigation revealed that the ancient people of Shali transported salt kerchief and salt mortar from the nearby Fetnass lake, 1 km distant, and not from Lake Aghormi (Fig. 1B).

Limestone and shale components are derived mainly from local hills lying near ancient Shali or from nearby Gebel EL Mawta (Death mountain). Date and olives seeds were used as additives within the mortar material: Siwa is famous for its date and olive production. Ancient bones and cattle bones were also reused as framework materials. The ancient Siwans manipulated their environment ecologically.

The fortress architecture depends on the substrate, relief and the basement composition. Builders used the original substrate as there is any pavement or restoration of the bedrock beds and along the layers of rocks (Fig. 3D). The ancient people also built the houses following bedding planes of the original rocks (Fig. 3E). Sometimes they engraved the muddy beds that intercalated the Miocene rocks as the ancient pharaohs did. They protected their ancient city by establishing high fences around the city encompassing their potable water wells and mosques.

5.2. *Diagenesis*

The main composition of Shali walls, roots and ceilings is evaporites. Evaporites are highly susceptible to extended and strong post-depositional diagenetic processes due to the highly reactive character of their chemical constituents (Orti-Cabo, 1976; Hardie et al., 1985; Schreiber and El Tabakh, 2000). The bulk of digenesis in Shali is due to the forced mechanism of salt mortar dehydration, particularly in summer. In consequence, in some places diagenesis was high, and many of the original fabrics and structures were obscured.

The process of diagenesis in this study includes transportation of salt materials from the nearby Fetnas Lake to Shali, the mixing of salt materials with sand and bentonite as a mortar and their pressing between framework components. The pressing leads to partial dewatering of the cement components, and subsequently compaction and lithification. This new situation led to acceleration of the diagenetic modifications i.e. dehydration, gypsum crystallization and halite cementation. Additionally, the resultant walls are subjected to many phases of diagenesis.

5.2.1. *Dehydration process*

After formation of the walls of Shali fortress, consequent processes of dewatering and dehydration occurred. These result from aeration and thermal insolation which led to drying of the walls and resulted in crystallization of evaporite minerals (principally gypsum and halite). The long term exposure of the external walls to these specific environmental conditions led to dramatic mineralogical changes including lithification, compaction due to overburden, and salt crystallization.

5.2.2. *Salt crystallization*

Diagenesis starts soon after deposition in very arid conditions in shallow hypersaline lakes of Siwa Oasis. Early diagenesis responds to conditions of the depositional environment (Schreiber and El Tabakh, 2000). Early diagenetic processes occur after the gypsum has been precipitated, but before it has been substantially transported and buried. Precipitation of gypsum began rapidly as a result of dewatering during transportation and also due to the evaporation regime. Early deformative phases of gypsum were formed during this stage. Squeezed clays are commonly formed.

The continuous crystallization of salts will proceed according to the repeated cycles of dissolution and precipitation that occur particularly in the winter season when high morning humidity is present (Rovero et al., 2009). The halite is in supersaturated solution and defused between the clay particles as very fine crystals, leading to tight binding of the framework. The strong adhesion and annealing crystallization which could be observed between the cement and the salt blocks is due to continuous crystallization through the epitaxial growth of sodium chloride. At the end of the process the kerchief blocks and the cement will be completely homogenous to a point that they apparently no longer be distinguished. The adhesion with limestone and shale fragments is less frequent, and salt is protruded inside the shale or within the fractured limestone (Fig. 4A).

The observed initial stage of diagenesis is gypsum mush that formed independent clusters and grew as hard consolidated rosettes along the margin of the walls or lining the walls and floors. The gypsum rosettes are planar or undulatory randomly distributed. Halite is precipitated as fine crystals, massive and nucleated in between the framework. The architecture of cement materials can be subdivided sedimentologically.

Gypsrudite consists of gypsum fragments of different sizes which are embedded in a matrix consisting of gypsum sand, carbonate silt, and mud. The primary character of such crystals as cleavage planes could be observed in some of these crystals along the walls of Shali fortress.

Gypsarenite is formed of poorly sorted gypsum (Fig. 4B) embedded in halite mud. The grain boundaries show minor interpenetration due to pressure solution. Some broken shell fragments consisting of silt-sized aggregates of carbonates are found scattered in gypsarenite (Fig. 4B, C). The shell fragments are clustered and found floating in a matrix of halite mud (Fig. 4D). Microspar is observed in the test cavities and encrusting their outer surface. The fine carbonate inside the shell fragments shows also some recrystallization into microspar in some places (Fig. 4D).

The crystals of halite have an almost unhedral equigranular polygonal mosaic-like texture. Some halite shows some interference colors due to pressure (Fig. 4D). They consist of more or less clear grains that meet at triple junctions and approach 120° angles (Fig. 4D). They have few inclusions, as most of the foreign materials are found at the halite boundaries during recrystallization (Kühn, 1968). Stanton and Gorman (1968) and Hardie et al. (1985) have concluded that such mosaic polygonal textures are a product of annealing crystallization, whereby grains optimize their size, shape, and orientation to minimize energy in the manner of bubbles in foam (Bathurst, 1975).

Deformation fabrics of cement materials were observed. The interpretation supports deformation textures seen in this study is being a result of overburden, local seismicity, ground instability and localized gravity faults. Heard and Rubey (1966) postulated that when gypsum is compacted, it becomes relatively soft, weak, and easily deformed because as pore-pressures near the amount of overburden pressure, the effective normal stress is reduced and gypsum becomes very prone to deformation. Fabrics of gypsum comprised of many twinned crystals often have an elongate and irregular appearance (Fig. 5A). The change from gypsum to anhydrite is obvious and observed as distinctive textures (Fig. 5B). Anhydrite replaces gypsum due to burial and or heat exposure. Most anhydrite pseudomorphosed both the grain shape and orientation of the original gypsum grain and is usually parallel to the gypsum cleavage planes, but a clear overprinting relationship is lacking. The degree of anhydrite replacement is locally variable but the majority retains much of the precursor gypsum (Fig. 5B).

Signs of intra-granular deformation are the development of periphery sub-grains and extensive undulose extension (Fig. 5C). As the grains of gypsum were sheared, dislocations developed producing undulose extinction (Schorn and Neubauer, 2011). The presence of selenite porphyroblasts is a rather good indication of deformation which typically has sutured anhedral grain boundaries and subgrain development on the periphery (Fig. 5C). The shape of the porphyroblasts is variable and ranges in size from millimeters to several centimeters. The contact between the groundmass and some porphyroblasts may be interpenetrating or straight. Holliday (1967) and Nanfito et al. (2008) proposed that evaporite porphyroblasts were the earliest form of secondary gypsum. They described the selenite porphyroblasts as having irregular boundaries and abundant relict anhydrite inclusions. Relict anhydrite inclusions were not evident in porphyroblasts of the current study, but irregular boundaries were recognized and appear consistent with

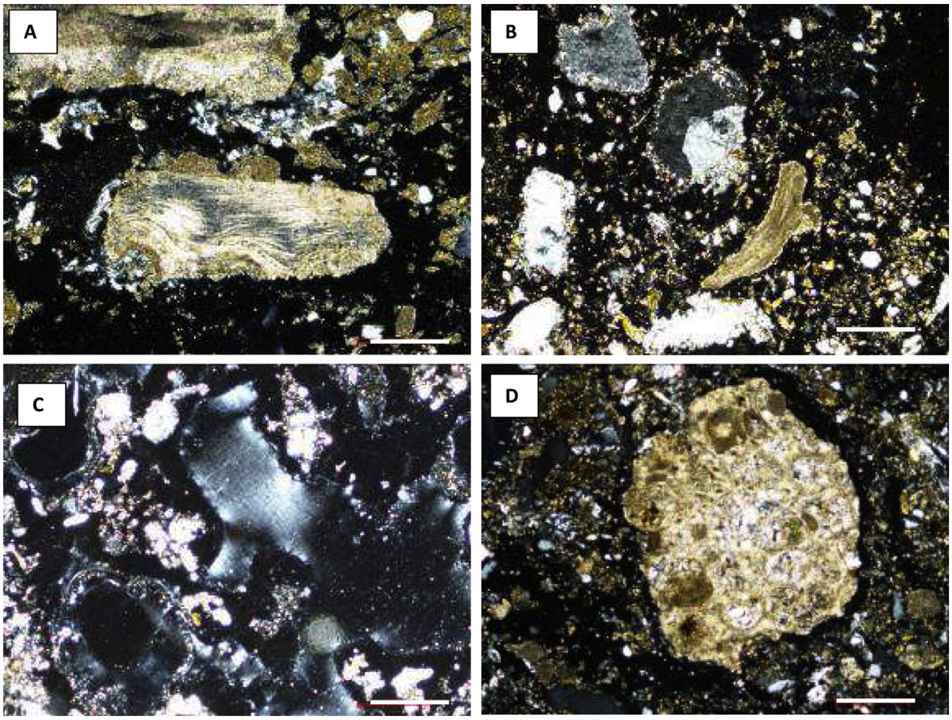

Fig. 4. A) Photomicrograph of limestone and algal shell fragments of Miocene age, detritus of gypsum and sand grains cemented by halite. B) Gypsarenite made up of anhedral and euhedral grains of gypsum and algal clasts embedded in halite groundmass. C) Silt and sand sized gypsum and organic structural materials cemented by halite mud. Notice interference color of the halite cement due to pressure, and D) Floating algal carbonate fragment and silt-sized clastics within halite mud cement. Scale Bar = 1000 μm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the development of sub-grains. They have a clear 'augen' shape and tails of recrystallized material that are coarser than the matrix (Fig. 5D).

5.3. *Differential weathering of Shali Fortress*

The salty walls of Shali fortress are exposed to various atmospheric effects (physical, chemical, and biological) including the water cycle of precipitation, saturation, and evaporation. The effects of diagenetic changes, principally cement distribution, kerchief blocks, and bentonitic clays, the most predominant groundmass, are accentuated during the weathering process. The prevailing mechanism of weathering may vary depending on rock lithology and climate. More than one phase of recent dissolution during the last century occurred in the study area, as documented in 1926, 1929, and 1953 (Cassandra, 2000).

The most effective rainy period in 1926 destroyed most of the houses and their walls, and left only ruins. This resulted in a number of cavities, fractures, bending and collapsing (Fig. 3A, B). The steady flow rates and high rates of evaporation seem to be critical for cavity formation (Turkington, 1998). After each heavy rainfall, a supersaturated solution is formed between salt cations and water within cavities and between frameworks of the wall materials, which assists in dissolution of halite and swelling behavior of bentonite (Fig. 5E, F). Additionally, the palm beams of the doors, windows, and walls act as conduits of the fluids as well as keeping the fluids within, leading to subsequent continuous dissolution of underling walls. Upon evaporation, the halite crystals are recrystallized in the pore spaces and voids. This recystallization exert stresses and cause mineral breakdown. The effect of evaporation not only leads to salt crystallization pressures but also shrinking and fracture of bentonite clays, causing separation of the framework of the Shali walls.

Clay flakes and fragments are highly observable in most of the cavity walls. XRD samples have shown that the most common clay mineral is bentonite (Fig. 6). Montmorillonite is the principal clay mineral phases present in these samples, identified by its d-spacing peak at about 14.5 A°. Subordinate amounts of kaolinite could also be identified. The bulk clay content rarely exceeds 15 vol.%.

The fluids, either saline or not, produce rock disintegration. The increase in intergranular pressure of salt crystal growth and or salt hydration results in crack widening and loss of contact between grains (Winkler, 1975; Goudie and Viles, 1997; Adamovic et al., 2011). The dissolution of clay matrix by saline fluids is enhanced (Young et al., 2009), with reaction with expandable minerals in rock matrix (Pye and Mottershead, 1995). Young (1987) and Pye and Mottershead (1995) note that salt, as a chemical weathering agent, may promote cavity development by dissolving silica grains with an alkaline solution. In Australian sandstone, Young (1987) used scanning electron microscopy to reveal that sodium chloride chemically etches silica grains and that this alkaline solution increases the rate at which quartz dissolves.

6. Conclusion

The Shali Fortress is one of the most unique and fascinating structures of ancient architecture. The houses are built with evaporite stones, either as kerchief blocks or cement. This type of architecture acts as a good heat insulator. The fortress is subjected to two main processes, diagenesis and differential weathering.

The process of diagenesis is manifested by: 1) transportation of salt mortars from Fetnas Lake to Shali site, 2) mixing the salt with sand and clays as a mortar and pressing in the pore holes between framework components, 3) partial dewatering of the cement components, and subsequently compaction and lithification. These processes led to acceleration of the diagenetic modifications i.e.

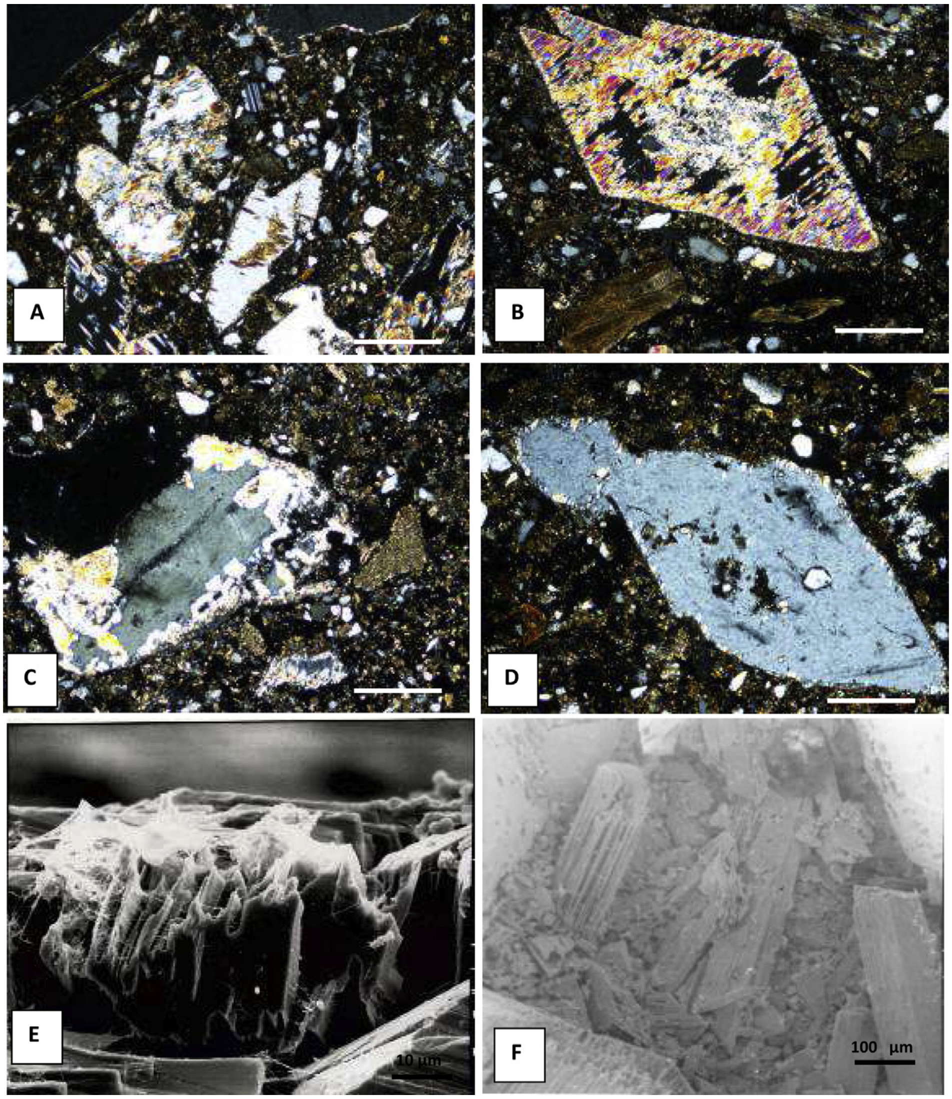

Fig. 5. A) Elongated and irregular twinned crystals of gypsum in association with anhydrite clasts and silt sized clastics embedded within halite mud cement. B) Twinned gypsum altered to anhydrite. C) Intra-granular deformation and development of periphery sub-grains and extensive undulose extension, D) Clear augen shape of gypsum with irregular boundaries and development of secondary anhydrite sub grains. E) Dissolution of halite crystal along the cleavage planes. And F) Distinct dissolution of gypsum and Halite accompanied by general decay, swelling and disruption of the associated bentonitic framework. Scale Bar = 1000 µm.

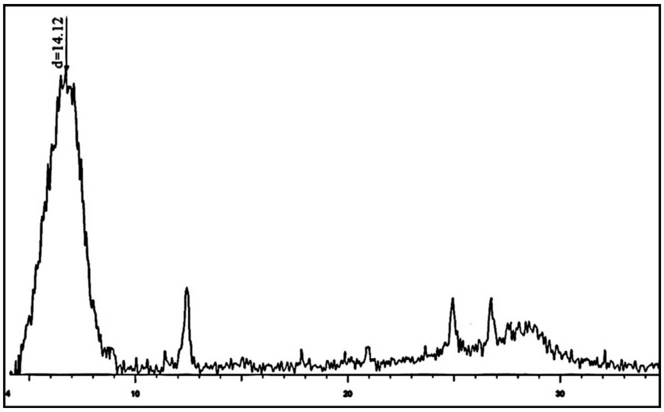

Fig. 6. XRD chart showing bentonite mineral (montmorillonite).

dehydration, gypsum crystallization, and halite cementation. Additionally, the resultant walls are subjected to many phases of diagenesis which include dehydration, thermal insulation, and salt crystallization. The strong adhesion and annealing crystallization which could be observed between the cement and the salt blocks is due to continuous crystallization.

The palm beams of the doors, windows, and walls act as conduits of the fluids, as well as keeping the fluids within, which lead to subsequent continuous dissolution of underlying walls. Upon evaporation, the halite crystals are recrystallized in the pore spaces and voids. The effect of evaporation not only leads to salt crystallization pressures but also shrinking and fracture of bentonite clays causing separation of the framework. The salty walls of Shali fortress are exposed to various atmospheric effects (physical, chemical and biological) including the water cycle of precipitation, saturation, and evaporation. The effects of diagenetic changes become accentuated during the weathering process. Ancient Shali has been subjected to more than one phase of recent dissolution and weathering during the last century, leaving ruins and collapsed houses.

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