Iraqi Bulletin of Geology and Mining Vol.7, No.1, 2011 p 39 – 53

PETROLOGY AND CHEMISTRY OF SOME EXOTIC ROCK FRAGMENTS FROM JABAL SANAM, BASRAH, IRAQ

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Received: 26/ 08/ 2010, Accepted: 29/ 12/ 2010
Key words: Hormuz Series, Sanam, Salt plug, Iraq

ABSTRACT

Petrologic and chemical analyses of 16 exotic rock samples collected from Sanam salt plug in southern Iraq showed igneous and sedimentary rocks of various types and origins. Highly magnesian igneous rock samples with forsterite composition of (Fo_{90-92}) mole% are the only igneous rock type found in this study. They are highly serpentinized and the alteration minerals are antigorite and talc. This is a mantle-derived subvolcanic rock, fragmented and brought to surface with the rising salt diapir.

Dark gray dolomite with possible stromatolitic structures is one of the common rock types at the Sanam plug. It is fine crystalline and partly silicified. It was probably precipitated in reducing environment on the flanks of the salt basin. Some pure recrystallized calcitic limestones were also recognized and seem to be of chemogenic origin; as parts of vein fillings.

Shale, with illite, as dominant clay mineral, and quartz with minor kaolinite and montmorillonite may represent ancient fluvial deposits. One sample was identified as silicified ferruginous mudstone with peculiar mineral composition of orthoclase, quartz, illite, hematite, goethite, gypsum and jarosite. The origin of this rock may be volcanic and include initial mud rich in feldspar, which was indurated and altered by microbial Fe precipitation and enrichment via colloidal state, gypsum cement was introduced later and silicification followed.

صخرية وكيميائية بعض القطع الصخرية المنقولة في جبل سنام، البصرة، العراق

خلدون صبحي البصام

المستخلص

يعتبر جبل سنام واحداً من أكثر من مائتين من المقحمات الملحية التي تعود إلى سلسلة هرمز في منطقة الخليج العربي والتي يقدر عمرها بتحت الكامبري. بينت دراسة صخرية وكيميائية لـ 16 عينة من الصخور المنقولة مع المقحمات الملحية وجود عدة أنواع مختلفة من الصخور ذات تراكيب ومناشئ مختلفة، نارية ورسوبية. تم التعرف على عينتين من الصخور النارية عالية المغنيسيوم بمحتوى من الفورسترايت يتراوح بين (90 – 92) mol% مع وجود عمليات تغير إلى السربنتين ونشوء معادن ثانوية ونتيجة ذلك هي الانتغورايت والتالك. تعتبر هذه الصخور من صخور الجبة الأرضية، وهي صخور فوق قاعدية تتكون من الاوليفين أساساً وتصنف على أنها شبه بركانية لتصلبها قرب سطح الأرض، ويعتقد ان أجزاء منها قد اقتطعت وصعدت مع الملح الصخري المندفع إلى الأعلى.

بينت الدراسة وجود شائع للدولومايت الرمادي الداكن، ناعم التبلور الذي أشارت دراسات سابقة إلى وجوده في هذه المقحمات في عدة مواقع في منطقة الخليج العربي. تحتوي هذه الصخور الرسوبية على تراكيب شبيهة بالستروماتولايت، ويعتقد انها ترسبت في بيئة بحرية على حافة الحوض الرسوبي. تظهر عمليات تغير إلى السيليكا واضحة في بعض هذه العينات مع وجود آثار للجبسم فيها. وأظهرت الدراسة وجود عينات من حجر الكلس معاد التبلور وعالي النقاوة وبدون أية تراكيب تدل على أن منشأه في بيئة بحرية ويعتقد انه ناتج ترسيب كيميائي مباشر من محاليل مشبعة قد تكون قد وجدت في الشقوق والفواصل مكاناً مناسباً للترسيب.

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وجدت عينة من السجيل يسود فيها معدن الإلايت والكوارتز مع وجود أقل من الكاؤولينايت المونتمورلونايت ومن المحتمل إنها رواسب قارية نهرية. كما أظهرت الدراسة وجود عينة تتكون من الأورثوكليز والكوارتز والجبسم والإلايت والهيماتايت والغوثايت والجاروسايت يحتمل إنها طين بركاني غني بالفلدسبار تعرض إلى عمليات تحويرية مختلفة من ترسيب للمعادن الحديدية بعمليات بايوكيميائية وعمليات التحام بالجبسم ثم التغير إلى السيليكا.

INTRODUCTION

Jabal Sanam is located south of Basrah city, almost on the Iraq – Kuwait borders and forms a topographic hill, about 150 m, a.s.l. (125 m, above surrounding area) and about 1.5 Km in diameter (Fig.1). It is formed of a single mount of older rocks surrounded by Middle Miocene – Pliocene rocks and Quaternary sediments, which form the surrounding flat plains.

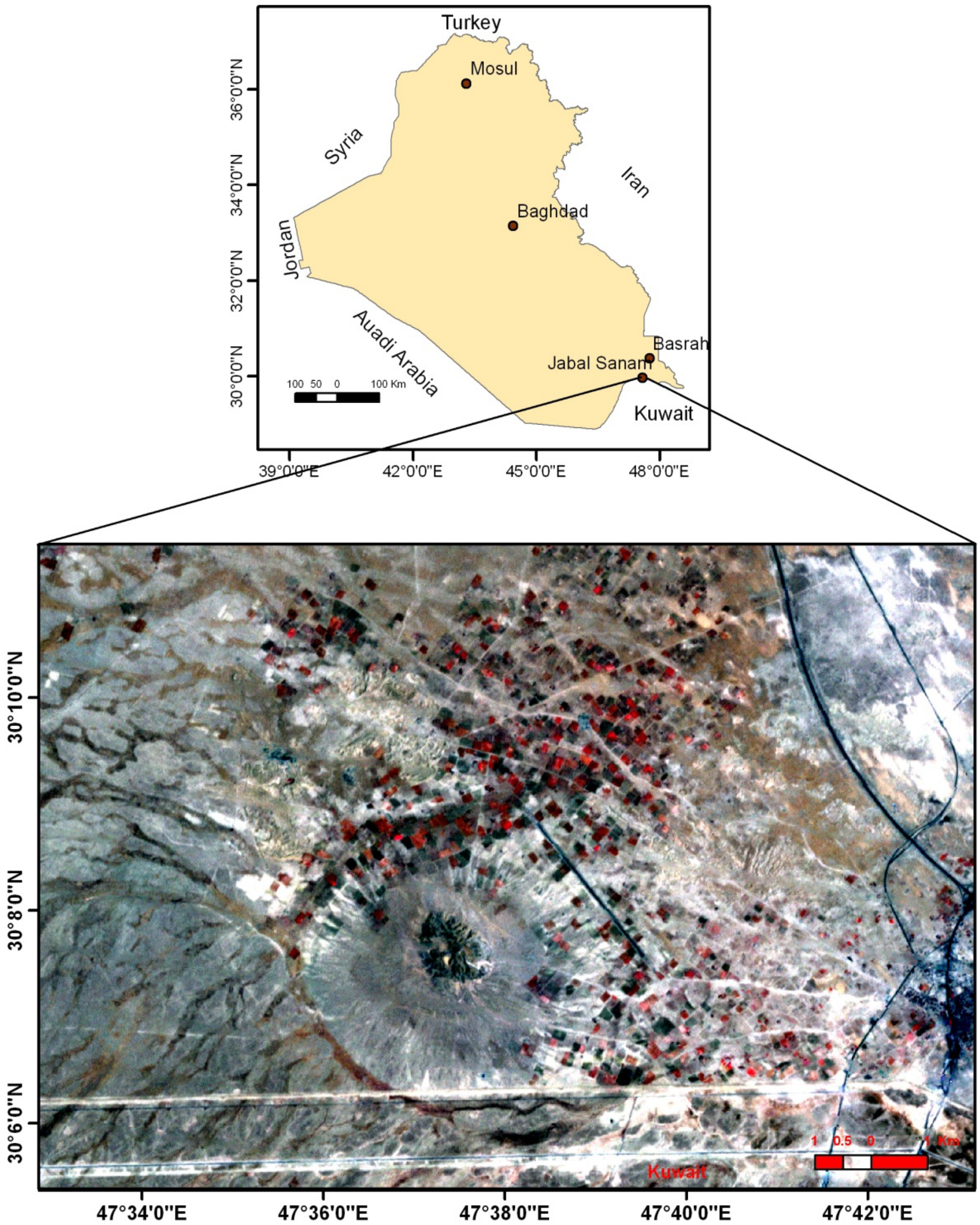


Fig.1: Location of Jabal Sanam

The mount body is comprised of a heterogeneous mixture of rafts and boulders of various lithologic compositions including igneous rocks, dolomite and shale, embedded in a gypsum/ anhydrite matrix (Al-Naqib, 1970 in Buday and Jassim, 1987). Dating of some dolerite rock fragments by K/Ar method revealed an age of (575 – 580) Ma, which give those specimens an Infracambrian or Cambrian age (Buday and Jassim, 1987). Moreover, the magnetic and seismic surveys, carried out by GEOSURV and former INOC, showed indications of the salt at depth, which supported the earlier suggestions that Sanam is a salt plug related to the Hormuz Series, and it is similar in origin to more than 200 islands in the Gulf region, believed to have formed by salt diapirism (Sadooni *et al*., 2004). The Hormuz Series was named after the Iranian island located in the Straits of Hormuz in the Arabian Gulf. The name "Hormuz Salt Formation" was introduced by Blanford (1872) in Alsharhan and Narin (1997).

▪ **Previous Work**

Little work has been done on the Sanam salt plug, but similar features in the Gulf States, Oman and Iran have received a lot of attention.

- Harrison (1930) mentioned that the extrusive salt has come to the surface at different periods from Oligocene to Pliocene.
- Kent (1970) in: Alsharhan and Narin (1997) described the Hormuz evaporitic series as repeated cycles of halite, gypsum, colored shale and dark dolomite with a variety of igneous rocks intercalations.
- Ala (1974) mentioned two periods of salt mobilization and intrusion: a pre-Zagros (pre-Alpine) Phase, possibly dating back to the Triassic, and a Late Tertiary syn-to post-orogenic phase. He estimated the rate of intrusion by about 2 mm/ year in the most actively rising diapirs. He mentioned igneous and metamorphic rocks association with the evaporites.
- Chisholm (1975) described the black foetid dolomite and dolomitic shale overlying the salt plug at Jabal Sanam and noticed both incipient and fully developed brecciation in these rocks, which were attributed to intense crushing.
- Kent (1979) stated that the extrusive salt plugs in the "gently folded zone" of the Zagros Mountain Belt are exclusively composed of Hormuz Series, carrying "exotic" blocks originating at depths of (3 – 5) Km, below surface and dated as Precambrian. Sedimentary and igneous (volcanic and intrusive) rocks were recorded.
- Buday and Jassim (1987) suggested that the dolerite fragments recorded from the breccia of the salt plug at Jabal Sanam belongs to the Infracambrian basic volcanic sequence and the strong epidotization of the dolerite may confirm the metamorphism of the Infracambrian sequence.
- Meneisy (1988) believed that a tectono-thermal event took place some 33 Ma ago according to K/Ar dating of some minor volcanic intrusions on the Halul Island in the Arabian Gulf. He reported the Hormuz rocks in the island to be composed of dolomitic limestone, gypsum, anhydrite and andesitic-type volcanic rocks.
- Husseini (1988) and Husseini and Husseini (1990) mentioned that during Precambrian and Cambrian (600 – 540 Ma) extensive left lateral faulting along the complex NW – SE trending Najd Fault System cut across the Arabian Shield. Extensive evaporitic basins developed in northern Pakistan, southern Oman, the Arabian Gulf and the Zagros Mountains. These evaporitic basins were interpreted as subsiding basins and were all sites of salt precipitation. They suggested that the syn-rift evaporites were first precipitated during a transgression, which commenced in the latest Precambrian (600 Ma) and again a Lower Cambrian regression. The regression terminated a period dominated by marine

carbonates and evaporites, and initiated the deposition of progradational alluvial to marginal marine sediments.

- Alavi (2004) reported that pull-apart basins were developed by the Najd strike-slip fault system.
- Fard *et al*. (2006) suggested that the "Early Cambrian" Hormuz salt represents the fundamental sole for the Zagros Fold-Thrust Belt and locates major faults propagation folds in the southwestern Dezful Embayment.
- Lacombe and Roure (2007) mentioned that the Hormuz Series have penetrated (7 – 9) Km of sedimentary rocks in the Fars domain, east of Zagros Mountain Range.
- Nasir *et al*. (2008) described abundant stromatolitic bedding in the dolomite rocks of the Hormuz Series in the Halul and Sharaouh salt plugs (islands) and suggested formation in reducing intertidal to supratidal environments.
- Farhoudi *et al*. (2010) mentioned that the salt plugs are distributed on the Arabian Platform along regional basement faults and have pierced cover rocks of up to 10 Km thick. Pieces of the basement have been brought up to the surface on some of the salt domes. The fragments were transported by rotational ascent of the "Hormuz Salt Formation" to the present and former land surfaces and some of the strike-slip faults have had important role in forming of pull-apart basin for uplift of salt domes.

▪ Sampling

In a short field trip to Jabal Sanam by the author and a group of GEOSURV geologists, about 20 rock samples were collected from the top and slopes of the hill. Being exotic, naturally disturbed and dislocated fragments, there was no way for systematic sampling; the samples were collected to cover as many rock types as possible. Sixteen of these samples were chosen for this study. They are described as follow:

- Sample 1: Igneous rock, dark gray and green color, with white fibrous talc patches, tough, fractured and serpentinized (Fig.2a).
- Sample 2: Igneous rock, light green with darker green fragments, brecciated with veins filled by quartz, serpentinized.
- Sample 3: Dolomite, dark gray, laminated, caverneous, fine crystalline, tough.
- Samples 4, 9, 8: Dolomites, gray, laminated, tough and fine crystalline.
- Sample 5: Dolomite, dark gray, brecciated and fractured, fine crystalline.
- Sample 6: Dolomite, dark gray, laminated, tough and fine crystalline (Fig.2b).
- Sample 7: Dolomite, gray, caverneous, fractured with quartz cement (Fig.2c).
- Sample 10: Dolomite, gray with brown tint, brecciated and cemented.
- Sample 11: Dolomite, white, gray and pale yellow, very tough, laminated and caverneous.
- Sample 12: Dolomite, dark and light gray, fragmented, with solution cavities, cemented by quartz (Fig.2d).
- Sample 13: Limestone, light gray and pink, tough, recrystallized.
- Sample 14: Limestone, light gray and white, tough, recrystallized and caverneous (Fig.2e).
- Sample 15: Shale, light gray, highly plastic.
- Sample16: Mudstone, orange, yellow and red, silicified and ferruginous, tough, caverneous (Fig.2f).

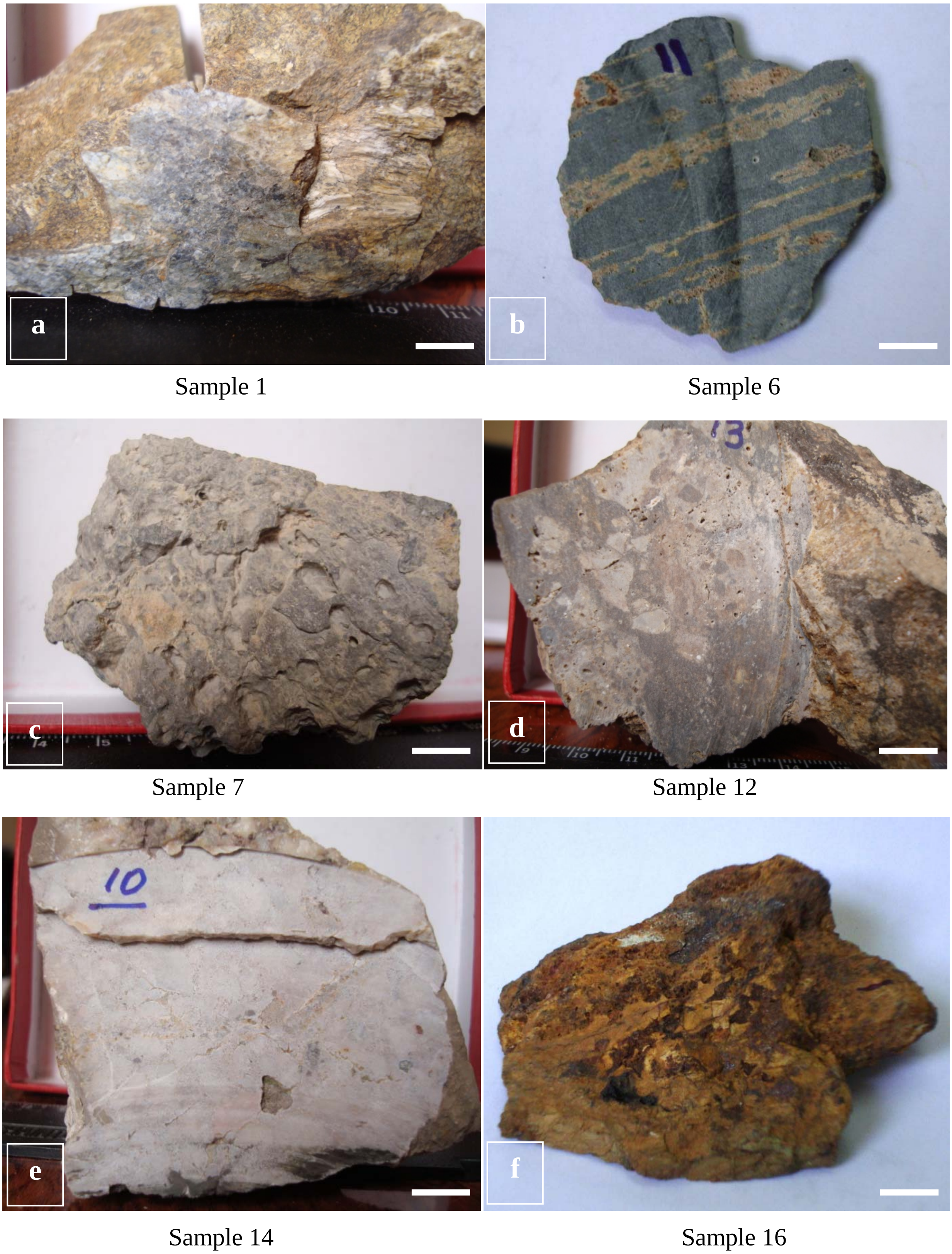


Fig.2: Hand specimens (bar = 1 cm)
(a) Igneous rock **(b)** Laminated dolomite **(c)** Dolomite with solution cavities
(d) Brecciated dolomite **(e)** Recrystallized limestone **(f)** Silicified ferruginous mudstone

- **Laboratory Work**

All samples were examined in thin sections using transmitted light polarized microscope. The same samples were analysed by X-ray diffraction, using Shimadzu XRD 7000 and were chemically analysed for major oxides: SiO_2, TiO_2, Fe_2O_3, Al_2O_3, CaO, MgO, K_2O, Na_2O and loss on ignition (L.O.I) at 1000º C. The igneous samples were analysed for FeO and Fe_2O_3. Sulfate was analysed in one sample only, but qualitatively looked for in the other samples. The methods used are standard procedures of GEOSURV, described in detail in Work Procedure, Part 21 (Al-Janabi *et al*., 1992). The analytical procedures include gravimetry for SiO_2 and L.O.I., atomic absorption using Varian AAS 240 FS for Fe_2O_3 and MgO, flame photometry for K_2O, Na_2O using Gallenkamp instrument, Colorimetry using Technicon Autoanalyser for Al_2O_3 and TiO_2, and titration methods for MgO > 15% and FeO.

RESULTS (Petrology and Chemistry)

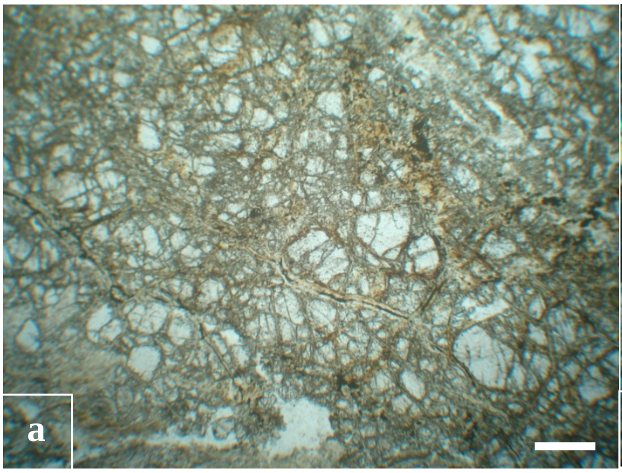
- **Petrology**

This study includes microscopic observations related to mineralogy, texture, diagenetic processes and alterations. The mineral composition is supported by XRD analysis (Table 1). The studied samples can be grouped into the following rock types:

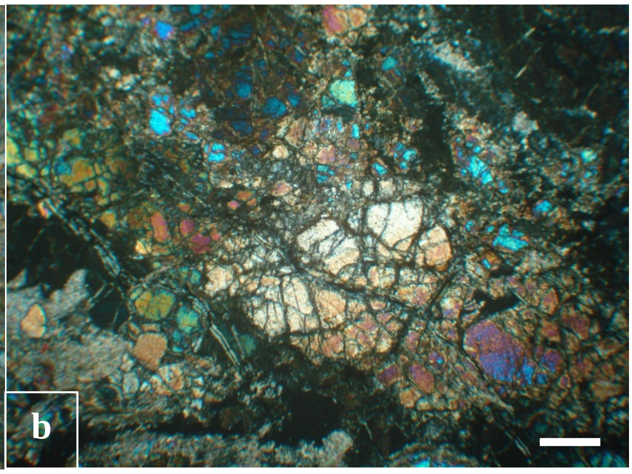
– **Igneous rocks:** Two samples only can be classified as igneous rocks (no.1 and no.2). They are composed of olivine (Fig.3a and b) with forsterite content (90 – 92) mol% (estimated from the X-ray scan using the 130 hkl peak and following the method of Yoder and Sahama (1957). Alteration minerals are serpentine (antigorite) (Fig.3c and d) and talc (Fig.3e). The olivine is highly fractured (Fig. 3a and b) and present as anhedral crystals (0.1 – 0.3) mm in size, as well as disseminated fine grains in the matrix. Rare hematite/ goethite grains were noticed and have suffered fracturing and alteration (Fig.3f). Alteration to serpentine and talc is considerable. Traces of halite and montmorillonite were noticed in the XRD scans of sample no.2. These two samples resemble limburgite in some respects (Hutton, 1943; Kraus *et al*., 1959; Cornen *et al*., 1996 and Encyclopedia Britannica, 2009). However, most limburgites are described with augite as a common mineral constituent. Pyroxene is absent in these two samples which are more similar to altered and fractured dunites.

– **Carbonate Rocks:** The majority of the studied samples are dolostones, and to a lesser extent limestones. The dolomite is fine crystalline (Fig.4a), laminated in some samples (Fig.4b) and contain detrital quartz (Fig.4c). Silicification is intense in some samples, where quartz fills cavities and fractures (Fig.4d). Some dolomite samples have suffered solution and exhibit many solution channels and cavities (Fig.4e). Traces of gypsum showed in the XRD scan in some dolomite samples (12 and 14). Apart of gypsum, detrital and diagenetic quartz is the only impurity.

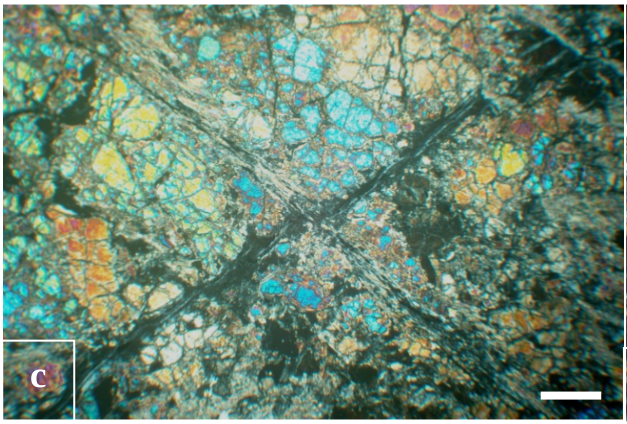
The limestones (13 and 14) are recrystallized with interlocking calcite crystals (up to 5 mm large), but generally are (0.5 – 1.00) mm in size (Fig.4f). These limestones are pure carbonates, composed almost entirely of calcite, with traces or no detritals and are barren of fossils.



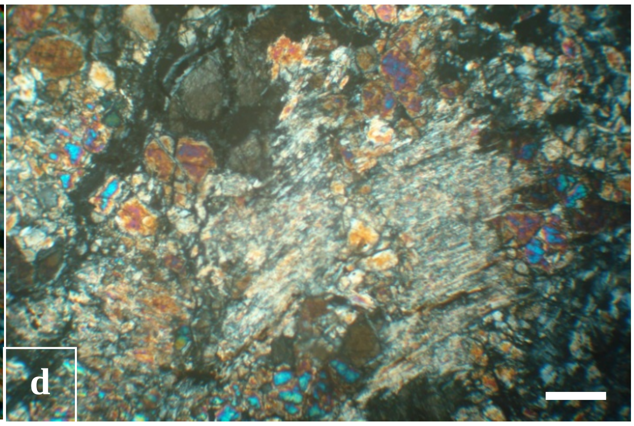
Sample 1



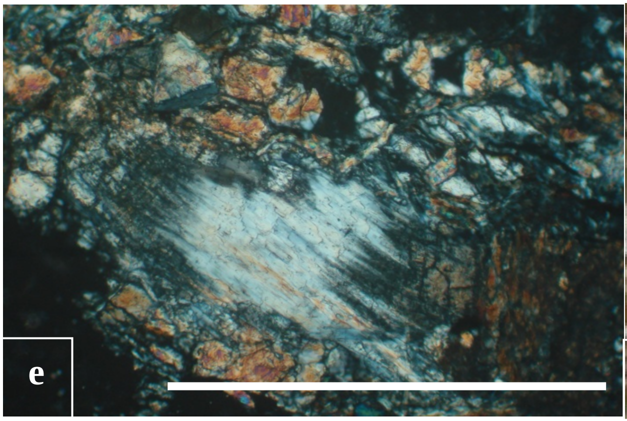
Sample 1



Sample 1



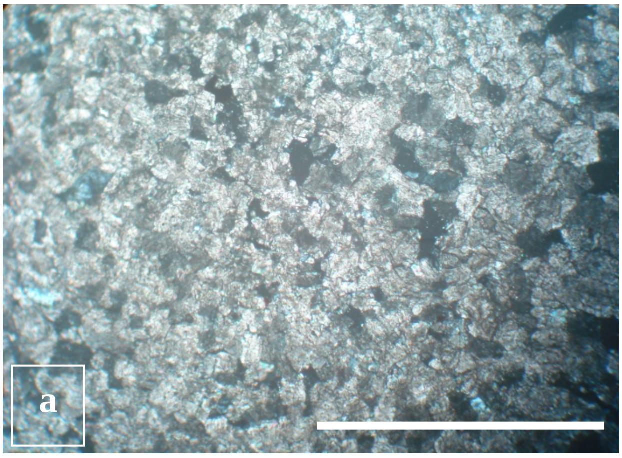
Sample 2



Sample 2

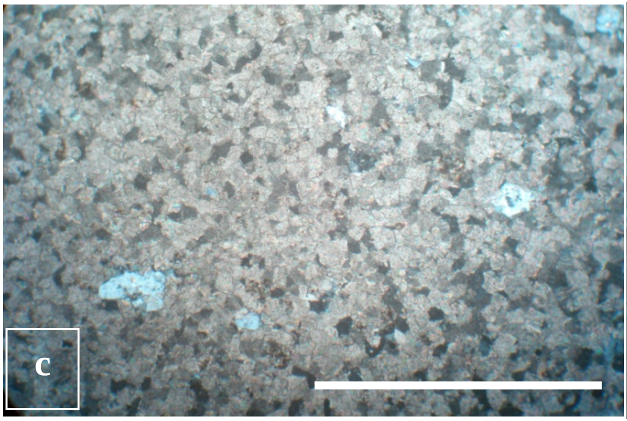
Sample 1

Fig.3: Igneous rocks micro textures (bar = 0.5 mm)
(a) Olivine (forsterite) fractured anhedral crystals (ppl)
(b) Same as (**a**) under XN
(c) Serpentinization along fractures (XN)
(d) Antigorite (fibrous) and olivine crystals (XN)
(e) Talc (white) and olivine crystals (XN)
(f) Hematite with solution channels (ppl)

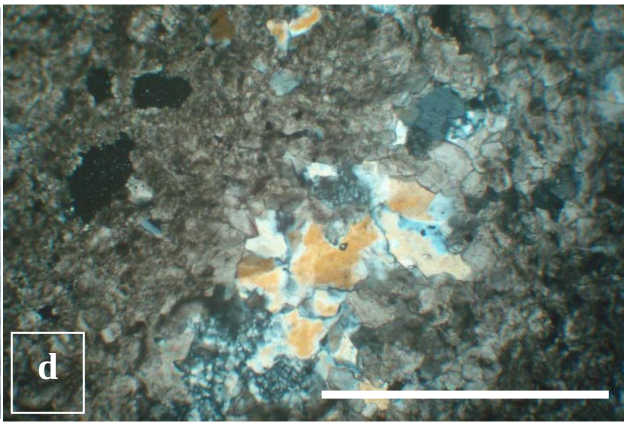


Sample 4

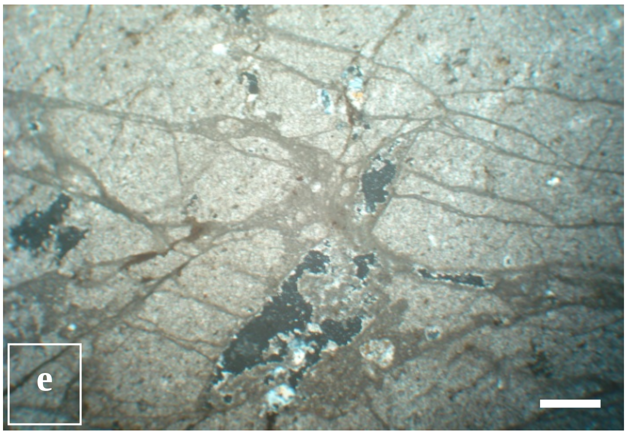
Sample 6



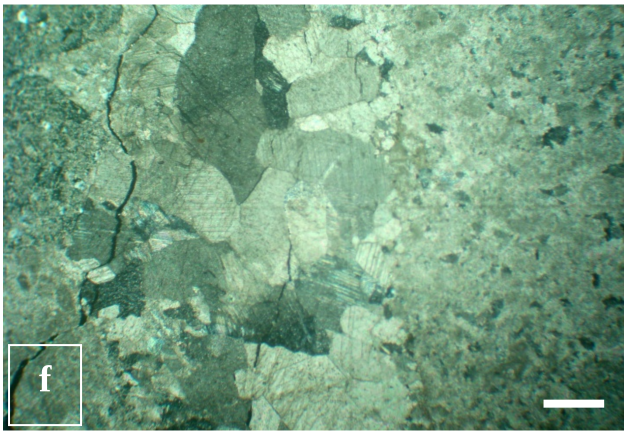
Sample 10



Sample 9



Sample 7



Sample 14

Fig.4: Carbonate rocks micro textures (bar = 0.5 mm)
(a) Dolomite, anhydral fine crystals (XN)
(b) Dolomite with dark laminations (ppl)
(c) Dolomite with detrital quartz (XN)
(d) Dolomite with quartz cement (XN)
(e) Dolomite with solution channels (XN)
(f) Recrystallized limestone (XN)

Table 1: Mineral composition (by X-ray diffraction analysis)

Sample no.	Mineral composition
1	Forsterite, Talc, Antigorite
2	Forsterite, Talc, Antigorite, Halite, Montmorillonite
3	Dolomite, Quartz (tr.), Microcline (tr.)
4	Dolomite, Quartz
5	Dolomite
6	Dolomite
7	Dolomite, Quartz
8	Dolomite, Quartz
9	Dolomite, Quartz
10	Dolomite, Gypsum, Quartz
11	Quartz, Dolomite
12	Quartz, Dolomite
13	Calcite
14	Calcite
15	Quartz, Illite, Kaolinite, Microcline, Montmorillonite
16	Orthoclase, Quartz, Hematite, Goethite, Jarosite, Illite, Gypsum

– **Shale and Mud Rock**s: One of the studied samples (15) is shale, or claystone. It is plastic and not amenable for thin section microscopic examination. The XRD scan shows quartz and clay minerals including illite (major), kaolinite (minor) and montmorillonite (trace). Traces of feldspar (microcline) was also detected (Table 1).

Sample 16 may be grouped under the category of volcanic mudstone, but with major diagentic modifications. The XRD analysis showed quartz and orthoclase as major minerals followed by gypsum, illite, hematite, goethite and jarosite. Under the microscope, it is composed of brown matrix with angular quartz inclusions, scattered without specific orientation (Fig.5a), and quartz cement in cavities. Iron oxide oncoids (microconcretions), of possible microbial origin, are noticed in cavities cemented by quartz (Fig.5b). Some features observed in cavity lining suggest colloidal state in the history of this sample. The feldspar detected in the XRD scan is obviously present as very fine submicroscopic crystals (or grains), together with gypsum, jarosite and Fe-oxides matrix. This sample seems to have gone through complicated and multiple histories of diagentic modifications.

▪ **Chemical Composition**

The chemical composition of the studied samples is shown in Table (2). The results are in good harmony with the mineral composition of these rocks. The high MgO and low SiO_2 contents of samples 1 and 2, together with the very low Al_2O_3, and negligible K_2O and Na_2O conform with a subsilicic ultramaphic igneous rocks, such as limburgite and dunite.

The relatively low Fe content supports the dominant forsterite composition of the olivine in these samples. However, the iron is considerably oxidized to Fe^{3+} in the alteration processes, especially in sample 2. The absence of feldspars is clearly shown in the negligible contents of alumina and the alkalies (Na_2O+ K_2O). Sample 2 may contain some secondary carbonate impurities, suggested by the CaO and L.O.I. contents. Both samples are rich in Ni, but not in Cr or Co (Table 2).

The carbonate samples are composed mainly of dolomite or calcite. The dolomite-rich samples show very high purity in some samples (3, 4, 5 and 6) with MgO content exceeds 20%. The only impurity is the variable amounts of detrital quartz expressed as minor amounts of silica in these samples (not exceeding 5% SiO_2), increasing in samples 8 and 9 on the expense of dolomite. Diagenetic cementation with silica had highly modified the chemical composition of these samples, where the dolomite content is reduced to about 60% in sample 11 and to about 30% in sample 12. The former includes some illite expressed as elevated contents of Al_2O_3 and K_2O, and also some Fe-oxyhydroxides, expressed by the elevated Fe_2O_3 content (Table 2). On the other hand, the limestone samples (13 and 14) are almost pure ($CaCO_3$ > 95%) with minor SiO_2 (as quartz mostly).

The shale composition is the highest in alumina and alkalies (especially K_2O) among the samples, supporting the dominant presence of illite. On the other hand, the silicified ferruginous mudstone (sample 16) shows iron and silica as the highest components related to secondary quartz and Fe-oxyhdroxide minerals (hematite and goethite) and jarosite. The SO_3 content is high (7.0%) in this sample, and corresponds to jarosite and gypsum. Potassium content is also high at 5.6% K_2O and corresponds to orthoclase, mica and jarosite.

DISCUSSION (Petrogenesis)

▪ Igneous Rocks

The studied samples (1 and 2) of this group show some similarities to limburgite and dunite with their remarkably high Mg-olivine being composed of forsterite (Fo_{90-92} mole%), absence of feldspar and hypocrystalline texture with subidiomorphic to idiomorphic olivine crystals. However, limburgite is reported in some literature, and in the type locality (Limburg, Germany) to contain pyroxene (augite) in considerable proportions (Rossenbush, 1872). The studied samples contain only forsterite with its alteration minerals. They represent subsilicic, subvolcanic, mantle-derived igneous rocks, which resemble altered dunites in mineral and chemical composition.

Forsterite (Mg_2SiO_4) is a high temperature mineral, among the first to crystallize from the melt (Hyndman, 1972). Pure forsterite is unknown in igneous rocks, but those with 90 mol% or more forsterite are known in dunites and limburgites. Forsterite-rich olivine is a common crystallized product of mantle-derived magma. Mafic and ultramafic igneous rocks are typically rich in forsterite end-member. Also, in metamorphosed dolostone and metamorphosed serpentine (Cornelis and Hurlbut, 1985 and Wilson *et al*., 2006).

The most Mg-rich olivines form in thermally metamorphosed impure limestone and dolostone (Deer *et al*., 1966). Forsterite was also reported in some meteorites, Moon and Mars rocks. More recently, it was discovered in biogenic deposits of biocorroded quartzite, where lichens were found to mineralize forsterite in situ, together with opal within microstramatolitic structures (Gorbushina *et al*., 2001).

Olivine is very susceptible to hydrothermal alteration, low-grade metamorphism and weathering (Deer *et al*., 1966). Among common alteration products are serpentine, talc, carbonates and Fe-oxides. The studied igneous samples have suffered considerable alterations, expressed as serpentinization of the olivine. Antigorite may be formed after forsterite (Deer *et al*., 1966). This alteration needs hydrothermal conditions (below 400º C) and oxidizing environment, which leads, among other things, to the oxidation of part of Fe^{2+} to Fe^{3+}, which is noticed in the chemical analysis of the studied samples. Antigorite may be altered to talc by further processes, especially in shear zones of serpentinized rocks and/ or by the metamorphism of dolomite (Deer *et al*., 1966).

Table 2: Chemical analysis (in wt%)

Sample No.	SiO_2	TiO_2	Fe_2O_3 *	Al_2O_3	CaO	MgO	K_2O	Na_2O	L.O.I.
1	41.36	<0.01	9.75	0.33	1.90	41.32	0.01	0.06	4.68
2	39.12	<0.01	7.60	0.33	6.79	35.01	0.04	0.25	10.83
3	2.92	0.06	0.50	2.90	28.32	20.17	0.46	0.12	44.53
4	4.50	0.05	0.48	0.28	28.48	20.17	0.17	0.15	43.96
5	1.20	0.05	0.43	0.29	29.43	20.56	0.23	0.18	46.12
6	5.00	0.08	0.78	0.55	28.68	20.06	0.48	0.17	44.19
7	3.60	0.05	0.58	0.50	29.44	19.80	0.39	0.25	44.59
8	9.10	0.09	0.43	0.80	27.70	18.62	0.79	0.24	42.09
9	8.06	0.08	0.36	0.44	28.30	18.23	0.44	0.24	42.63
10	10.70	0.10	5.56	1.86	27.76	13.99	1.20	0.19	35.84
11	22.55	0.19	2.95	2.80	21.92	13.49	1.85	0.33	31.55
12	59.54	0.11	0.90	1.60	12.49	7.76	0.05	0.12	16.59
13	1.92	0.09	0.24	0.29	53.43	0.45	0.05	0.09	42.64
14	3.18	0.10	0.44	0.39	52.14	0.52	0.07	0.09	41.95
15	58.99	0.54	4.30	12.69	1.90	7.38	6.70	1.28	4.25
16	29.74	0.38	30.04	8.45	6.65	0.31	5.60	0.95	11.01

* Total Fe as Fe_2O_3,
sample 1 contains 4.60% Fe_2O_3 , 4.65% FeO, 86 ppm Cr, 83 ppm Co and 1827 ppm Ni
sample 2 contains 4.60% Fe_2O_3, 2.69% FeO, 191 ppm Cr, 67 ppm Co and 1508 ppm Ni
sample 16 contains 7.0% SO_3

Sample 16

Sample 16

Fig.5: Silicified ferruginous mud rock (bar = 0.5 mm)
(a) Quartz (white) in Fe-rich illite and feldspar matrix (ppl)
(b) Fe oncoid, showing microbial structures cemented by quartz (white) in a cavity, surrounded by brown matrix with collform boundary (ppl)

The texture, mineralogy and chemical composition of the studied samples suggest a subvolcanic origin, where the melt cooled at shallow depths below the surface. The parent magma may have been a highly magnesian melt produced as a refractory residue left after the extraction of basalt magma in the upper mantle. It could have also formed by the accumulation of olivine crystals on the floor of large basaltic or picritic magma chambers resembling in this respect the cumulate dunites described by Blatt and Tracy (1996). The high Mg olivines and the absence of pyroxene and feldspars, as well as the high Ni content in the studied samples support these suggestions.

These rocks with their texture, mineral and chemical compositions are ultramaphic mantle-derived subvolcanic rocks. They are comparable in mineral and chemical composition to dunites (plutonic) and komatiites (volcanic) (Donaldson *et al*., 1986 and Hill *et al*., 1990), but were cooled at shallow depths. They may be related to the development of the pull-apart basins formed in the Late Precambrian or Early Infracambrian. They were fragmented and brought to the present surface at Jabal Sanam with the piercing salt plug of the Hormuz Series and have been transported through some 10 Km thick sedimentary cover where they were subjected to intense brecciation and alteration.

- **Carbonate Rocks**

The dark colored dolostone seems to be common in many salt plugs of the Arabian Gulf, Oman and Iran. They seem to be an essential and consistent part of the Hormuz Series. The dark color suggests formation in reducing environment. Some of the observed lamination of irregular shape, observed in some dolomite samples of the present study may be compared to similar structures noticed by Nasir *et al*. (2008) at Halul and Shraouh plugs, and were attributed to stromatolitic bedding and algal mats. These structures may be considered evidence of formation in intertidal to supratidal environments supported by the very fine grained texture of the dolomite. These dolomites might be earlier than or congruous with the evaporites of the Hormuz Series; they could have precipitated (directly or in the early digenesis) during the latest Precambrian transgressive phase (600 Ma), before the Early Cambrian regression, as marginal marine carbonates, whereas the evaporites occupied the center of the basins and continued to form longer time than the carbonates during the regressive and evaporitic phase.

The limestone samples are so calcitic and less affected by diagenetic modifications (except partial recystallization) that may suggest them as by-product of other rock alterations and/ or direct precipitation from solution in continental environments. They have no fossils content and no impurities or structures that may point towards their origin in marine environment. They might be broken parts of epigenetic vein filling.

- **Shale and Mudstone**

The shale (claystone) sample (15) is obviously of younger age and is dominated by illite which could indicate weathering of micaceous (muscovite-rich) rocks of any origin. The minor or trace presence of kaolinite and montmorillonite may reflect the aridity of the environment and the minor role of chemical weathering. The high plasticity of the sample may indicate less distance of transportation with the piercing salt plug and no metamorphism due to great burial or thermal effects. The studied shale sample, with its mineral composition, seems of continental fluvial origin.

On the contrary, the silicified ferruginous mudstone (sample 16) suggests formation in a weathered terrain with source rocks rich in feldspar. It might have been originally a volcanic mud rock. Iron have apparently been introduced in a later stage of diagenesis. The matrix is mostly orthoclase, Fe-oxyhydroxide, gypsum and jarosite. Quartz was introduced in a later stage as cementing material. Evidence of microbial origin of some iron oncoids or micro concretions were noticed in cavities cemented by quartz. The silicification might have attacked an earlier gypsum cement during a later stage of diagenesis, where silica-rich solutions silicified these rocks and increased their toughness. The history of diagenetic modifications might have been as follow (from older to younger):

1. Deposition of feldspar-rich volcanic mud or weathering of feldspar-rich parent rocks.
2. Iron precipitation (as oxides or sulfide) in swamps (?) by microbial processes (oncoids and concretions).
3. Gypsum cementation in arid climatic conditions and oxidation of pyrite (if any).
4. Silicification of gypsum/ anhydrite and introduction of quartz to the matrix.

CONCLUSIONS

- A variety of exotic rocks of various origins collected from Sanam salt plug have been identified and studied for the first time. They are: highly magnesian igneous rocks, dolomite, limestone, shale and silicified ferruginous and feldspathic mud rock.
- The igneous rocks are composed of highly fractured Mg-rich olivine (Fo $_{90-92}$) mol% and its alteration minerals produced by serpentinization processes, which are antigorite and talc. These are mantle derived, subvolcanic rocks with dunite composition, brought to the surface by the piercing salt of the Hormuz Series.
- The dolomites are similar to most dark gray dolomites reported and described in association with the Hormuz Series salt plugs of the Gulf region. They show some stromatolitic structure, and appear to have precipitated in reducing environment at the margins of the salt basin.
- The limestones are recrystallized, pure calcite and may be by-products of alteration processes or parts of large vein fillings. No evidence could be seen to support a marine origin for these samples.
- The shale is dominated by illite and quartz with minor or traces of kaolinite and montmorillonite. It seems to be of continental (fluvial) origin.
- The silicified ferruginous mudstone had undergone a series of diagenetic modifications. Originally it was probably a weathered feldspar-rich rock, which was later ferruginized, cemented with gypsum and finally silicified. A volcanic mud origin for this sample may be also considered.
- The results of the present study do not necessarily discredit previous results on the petrology of exotic rock fragments found at Jabal Sanam. The present work is a contribution and additional knowledge on the various types of rocks brought to the surface by the salt plug at Jabal Sanam.

ACKNOWLEDGEMENTS

The help provided in field work and sample collection by Dr. Saffa Fouad and Mr. Varoujan Sissakian is highly appreciated. The comments on the manuscript by Dr. Mohamad Isam and Dr. Khalid J. Aswad were very useful. Thanks are due to Miss Zainab Haddu for typing the manuscript, Miss Basma Asa'ad for microscope photography and for Mr. Hayder Hafedh for photographs editing.

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