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THE SEDIMENTARY IRONSTONE DEPOSITS IN THE WESTERN DESERT OF IRAQ: AN OVERVIEW

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ABSTRACT

Two main sedimentary ironstone deposits are investigated in the Western Desert of Iraq; the Ga'ara and the Hussainiyat deposits. The former is found within the fining-upwards successions of the Ga'ara Formation (Permocarboniferous) and the latter within the Clastic Unit of the Hussainiyat Formation (Lower Jurassic). Both deposits are continental, deposited in fluvial systems (meandering rivers represented by channels and floodplain deposits with lakes and marshes, with lateritic characteristics. They are mostly pisolitic-oolitic, concretionary, fragmentary and massive in texture and composed of goethite and hematite in association with kaolinite and quartz. The source rocks are highly weathered igneous, metamorphic and older sedimentary rocks of the Arabian Shield, transported by rivers to the depositional sites. The ironstone resources are limited (~80 m.t.) and the grade is low (<40% Fe_2O_3) with high contents of kaolinite and quartz impurities. Two open pit mines in the Ga'ara and Hussainiyat deposits have been operating since the early nineties to supply the cement industry in Iraq.

رواسب الحديد الرسوبي في الصحراء الغربية، العراق: نظرة عامة

فرج حبيب طوبيا و خلدون صبحي البصام و مازن يوسف تمار اغا

المستخلص

هناك راسبين اساسيين من الحديد الرسوبي في الصحراء الغربية تم إجراء التحري والتنقيب فيهما هما راسب الگعرة وراسب الحسينيات. الاول يوجد ضمن فتاتيات تنعم نحو الأعلى لتكوين الگعرة (البيرموكاربوني) والثاني ضمن الوحدة الفتاتية لتكوين الحسينيات (الجوراسي الاسفل). كلا الراسبين من أصل قاري ترسبا في بيئات نهرية مختلفة (التواءات نهرية ممثلة بترسبات القناة والسهل الفيضي والبحيرات والاهوار) مع تاثيرات للتجوية الكيميائية وخاصة في الراسب الثاني. يتكون النسيج الصخري لمعادن الحديد في هذه الرواسب من الحمصيات والمتكسرات واالتكتلات الحديدية التي يسود فيها معادن الغوثايت والهيماتايت مع الكاؤولينايت والكوارتز. تمثل الصخور النارية والمتحولة والرواسب القديمة المتعرضة للتجوية الكيميائية والتعرية في الدرع العربي الصخور المصدرية الاساسيه لهذه الرواسب حيث نقلت بواسطة الانهار الى مواقع الترسيب. تعد المصادر المعدنية الاقتصادية للحديد الرسوبي محدودة من ناحية الاحتياطي (حوالي 80 مليون طن) والنوعية (اقل من 40% اوكسيد الحديد) مع نسب عالية من شوائب الكاؤولينايت والكوارتز. يوجد مقلعين للحديد الرسوبي أحدهما في الكعرة والثاني في الحسينيات لإنتاج خامات الحديد لصناعة الاسمنت.

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INTRODUCTION

This review paper is based mainly on the results of extensive geological mapping and mineral exploration for ironstone deposits in the Western Desert of Iraq, carried out by Iraq Geological Survey since the early sixties of the past century. The information here is based on two published papers, namely Al-Bassam and Tamar-Agha (1998) for the Hussainiyat ironstone deposit and Tobia *et al*., 2014) for the Ga'ara ironstone deposits. Moreover, further information was taken from several unpublished reports on the geological survey, mineral exploration and excavations, such as Vasiliev *et al.* (1964); Tamar-Agha (1986 and 1991) on the Ga'ara deposits and Etabi and Dimitrov (1982) and Etabi *et al.* (1985) on the Hussainiyat deposit.

The sedimentary ironstones of Iraq are located in the Western Desert (Inner Platform of the Arabian Shelf). There are two main deposits of ironstones: (1) the older is the Ga'ara Formation (Permocarboniferous) and (2) the Hussainiyat (Lower Jurassic) deposits, in addition to numerous exposures of Jurassic ironstone near the Rutba town. The Ga'ara ironstone deposits and occurrences occur in the uppermost part of the Ga'ara Formation exposed at the Ga'ara Depression, some 65 Km to the north of Rutba town (Fig.1). Outcrops of the ironstone occurrences are exposed in more than nine hillsides along the southern rims of the Ga'ara depression, which extends for ~60 Km in the EW direction and has a width of ~30 Km. The ironstones were discovered in the 1960's and investigated at that time by Vasiliev *et al.* (1964) and Abboud and Mansour (1965). Several investigations followed subsequently (e.g. Technoexport, 1965; Chaikin, 1970; Yakta, 1972 and 1981; Lange, 1975; Etabi and Dimitrov, 1982; Tobia, 1983; Sadiq, 1985; Etabi *et al*., 1985; Tamar-Agha, 1986 and 1991; Maiqeel and Tamar-Agha, 1987 and Al-Youzbaki, 1989).

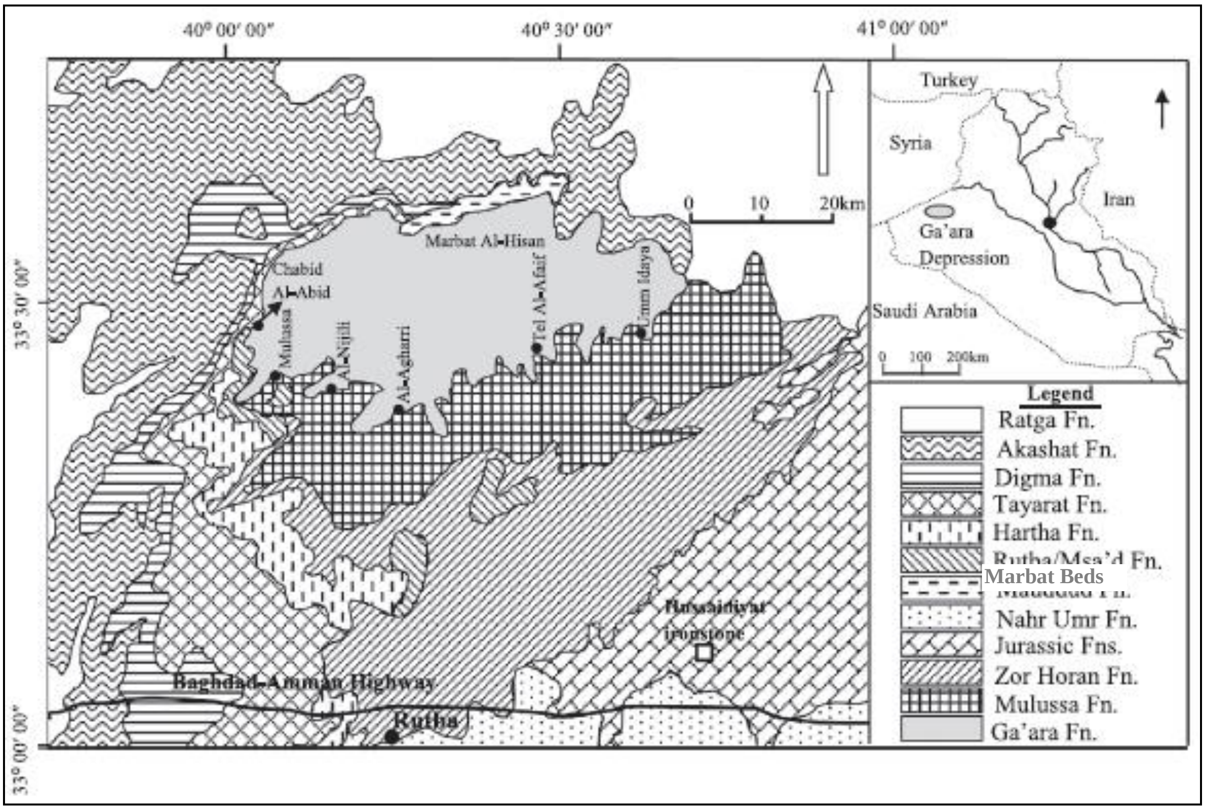

Fig.1: Geological map of the Western Desert of showing the Ga'ara and Hussainiyat ironstone deposits, (after Jassim *et al*., 1987)

The Hussainiyat ironstone deposit is remarkable for being one of the rare Jurassic sedimentary ironstone deposits in the Arabian Peninsula (Petranek and Jassim, 1980). The deposit is located in the Western Desert of Iraq, within the Hussainiyat Formation, which is exposed along the southeastern cliffs of Wadi Al-Hussainiyat to the southeast of Ga'ara Depression. The ironstone deposit is restricted to the southern part of the wadi.

The occurrences of sedimentary ironstone in the Rutba area are located about 20 Km to the east of Rutba town (Fig.1). They are covered by thin soil (less than 0.6 cm) and patchy tough calcrete, (0.2 – 6.0) m thick, associated with clayey and sandy sediments and consist of ooids, pisoids, and iron concretions. They are described by Al-Naqib *et al*. (1984 and 1986) as surficial deposits and considered to be the stratigraphic continuation of the Lower Clastic Unit of the Hussainiyat Formation in the Western Desert. They were compared with the Fe-laterite occurrence at Km 55 along Rutba – Baghdad highway, found at the unconformable surface of the Muhaiwair (Bathonian) Formation as small lenses comprised of inhomogeneous mixture of ferruginous sandstones and kaolinitic claystones.

PREVIOUS STUDIES

Vasiliev *et al.* (1964) reported that the Ga'ara ironstones are present in seven isolated locations, most of them at the southern rim of the depression. The ore is timed with the late stage of the deposition of the Ga'ara Formation. The geological investigation resulted in the assessment of brown hematitic iron deposits. Technoexport (1965) studied the Ga'ara ironstone in different localities, and concluded that the western location represents the hematitic ore, the southern is of bean brown iron ore and the eastern location, from the trenches, represent hematitic – limonitic ore. Chaikin (1970) divided the Ga'ara iron ore into two types: meager ore, characterized by high silica content and iron content between (20 to 40) %; and rich ore that is restricted to the exposures where the Fe content is more than 50%, enriched by weathering under arid climate.

Etabi and Dimitrov (1982) investigated the Hussainiyat deposit and made preliminary assessment of its ironstone resources. Early researchers believed that the Hussainiyat pisolitic ironstones are of shallow marine origin (Vasiliev *et al*., 1964; Skoček *et al*., 1971; Buday and Hak, 1980). In contrast, later researchers were more inclined towards a continental deposition (Petranek and Jassim, 1980; Jassim *et al*., 1981; Al-Hashimi and Skoček, 1981; Yakta, 1981, 1984; Tobia, 1983; Al-Bassam and Tamar-Agha, 1998). Lateritic processes were mentioned by some of these workers as a plausible factor in the ore formation (Petranek and Jassim, 1980; Al-Bassam and Tamar-Agha, 1998), whereas others emphasized the role of algae and bacteria (Al-Hashimi and Skoček, 1981). Petranek and Jassim (1980) are the first to reject the marine origin of the Hussainiyat ironstones. They considered the ore to be continental and residual in origin, mechanically washed, as clasts, into favorable depressions, partly of karstic origin, where they were preserved, except for some reworking by occasional "marine ingressions". They also recognized the in situ growth of the iron pisolites, whereas, some researchers believed that these pisolites formed in a highly agitated environment (Skoček *et al*., 1971; Tobia, 1983; Tobia *et al*., 2014).

Most of the previous researchers suggested a nearby source of the iron and associated clastics. The Ga'ara Formation, exposed at the northwest (Fig.1), is suggested as a possible source (Yakta, 1981, 1984; Tobia, 1983). Unspecified rocks of the Nubio-Arabian Shield were also suggested as a source (Skoček *et al*., 1971; Al-Bassam and Tamar-Agha, 1998). Sadiq (1985) divided the ironstones in the Ga'ara Depression according to mineralogical and textural study to massive ironstone, pisolitic-oolitic deposits and iron-bearing rocks. The origin of iron is believed to have resulted from weathering of parent rocks under tropical, humid climate during kaolinite formation in the source area. Iron was transported by rivers, adsorbed on the surfaces of clay minerals as ferric hydroxides, and then precipitated with clays on the river overbanks (Sadiq, 1985; Tamar-Agha, 1986 and 1991). Alsayegh *et al*. (1994) analyzed 54 samples from the Ga'ara Formation for their iron oxides content and they found that the total iron content ranges between (0.64 – 63.01) %, Fe_2O_3 (0.6 – 62.19) % and FeO (0.04 – 0.82). Iron is found as aggregates of oxides and hydroxides in different forms and structures like pisolites, concretions, slabby, vermiform, ferruginous beds, mottles, roots, rootlets, plant remains and boring fillings. Sadiq (1985) and Tamar-Agha (1986 and 1991) believe that the ironstone was formed at least in two stages: syndepositional and diagenetic.

The reserves of the ironstone in the Hussainiyat deposit were estimated by various groups of Iraq Geological Survey (Etabi *et al*., 1985, Abboud, 1990, Al-Qazzaz and Al-Ise, 1992, Mahdi and Husein, 1993 and Husein and Jassim, 1993). On the other hand, the work of Vasiliev *et al.* (1964) and Abboud and Mansour (1965) on the Ga’ara deposits were followed up several years later by further investigations. Small ironstone reserves at the Ga'ara Depression were estimated for cement industry by Maiqeel and Tamar-Agha (1987) and later by Jassim and Abdul Amir (1998). The deposits are almost exhausted now.

GEOLOGICAL SETTING

Iraq lies in the border zone between the two main Phanerozoic units of the Middle-East; the Arabian – African Platform and the Asian branches of the Alpine orogenic belt, expressed in Iraq by the Taurus – Zagros mountain ranges. The Western Desert of Iraq is part of the Stable Shelf of the Arabian Plate (Buday, 1980) and considered as the Inner Platform in the more recent tectonic subdivisions of Iraq (Fouad, 2012). The regional Rutba Uplift (Horan High) is the backbone and the main structural element of the Western Desert, dipping gently in the SE in comparison to the steeper NW side. The Ga'ara Depression is the most pronounced geomorphological feature in the region. It was considered as an anticline or dome in the early works (e.g. Buday, 1980 and Buday and Jassim, 1987) and later modified to a monocline by Tamar-Agha *et al.* (1997) and Tamar-Agha and Abdullah (2013).

The Ga'ara Formation (Permocarboniferous) is the oldest exposed formation in the Western Desert of Iraq, occupying the core and the inner rims of the Ga'ara Depression. The Ga'ara Formation consists of fining-upwards successions starting with sandstone that is pebbly in places, grading upwards into siltstone, kaolinite-dominated claystone that in many cases ends with a layer of ironstone, particularly in the uppermost part of the formation, at the northwestern and southern rims of the Ga'ara Depression. These fining-upwards successions are fluvial sediments deposited by meandering rivers. The sandstones of the Ga'ara Formation represent the channels of the rivers, whereas the mudstones represent the river overbank deposits, lakes and abandoned channel sediments (Tamar-Agha, 1986). The maximum exposed thickness of the Ga'ara Formation in the southern rim of the Ga'ara Depression near Tel Al-Afaif is ~100 m (Tobia, 1983), but the total thickness of the formation, including the subsurface counterpart, may reach 770 m (Buday and Hak, 1980). The age of the formation is considered as Permocarboniferous by Ctyroky (1971) based on the study of the plant remains. The Ga'ara Formation is unconformably overlain by the Upper Triassic to Paleogene formations. The Mulussa Formation (Upper Triassic), which consists of thick well-bedded dolostone, calcareous dolostone, and dolomitic limestone, is overlaying the Ga'ara Formation at the southern rim of the depression (Fig.1). At the northwestern rim of the depression the Ga'ara Formation is overlain by the sandstones of the Upper Cretaceous Rutba Formation and carbonates of the Ms'ad Formation (Middle Cretaceous) and in the northeastern rim by the Digma (Upper Cretaceous), Akashat (Paleocene) and Ratga (Eocene) Formations, which are comprised of carbonates-phosphates-shale associations (Fig.1). The sediments of the Ga'ara Formation are derived from plutonic-metamorphic complexes of the Arabian Shield as well as older sedimentary rocks (mostly siliciclastics) transported by rivers and then deposited in continental (fluviatile and lacustrine) environments with possible near shore and wind action contribution (Philip *et al*., 1968; Salman, 1977; Radosevic and Lesevic, 1981; Tobia, 1983; Sadiq, 1985; Tamar-Agha, 1986 and 1993; Tobia *et al*., 2014).

The Hussainiyat ironstone deposit is located east of the Rutba Uplift and lapping over it; where the Jurassic strata are exposed, striking NE – SW and dipping towards SE, forming a regional monocline. Block faulting is the main structural character of the area; the main system is NW – SE (Buday and Hak, 1980; Jassim *et al*., 1981). These faults have developed horsts and grabens, oriented in the same direction. The age of the formation is considered as Middle Liassic by Jassim *et al.* (1984) and as Bajocian by Hassan (1985). The latter dating was based on macrofossils whereas the former was based on stratigraphic position. The Hussainiyat Formation consists of two main lithological units: the lower unit comprises kaolinitic mudstones and sandstones with ironstone horizons or lenses restricted to the southern exposures of the formation. The upper unit is a dolostone with chert nodules, sandy at base (Fig.2).

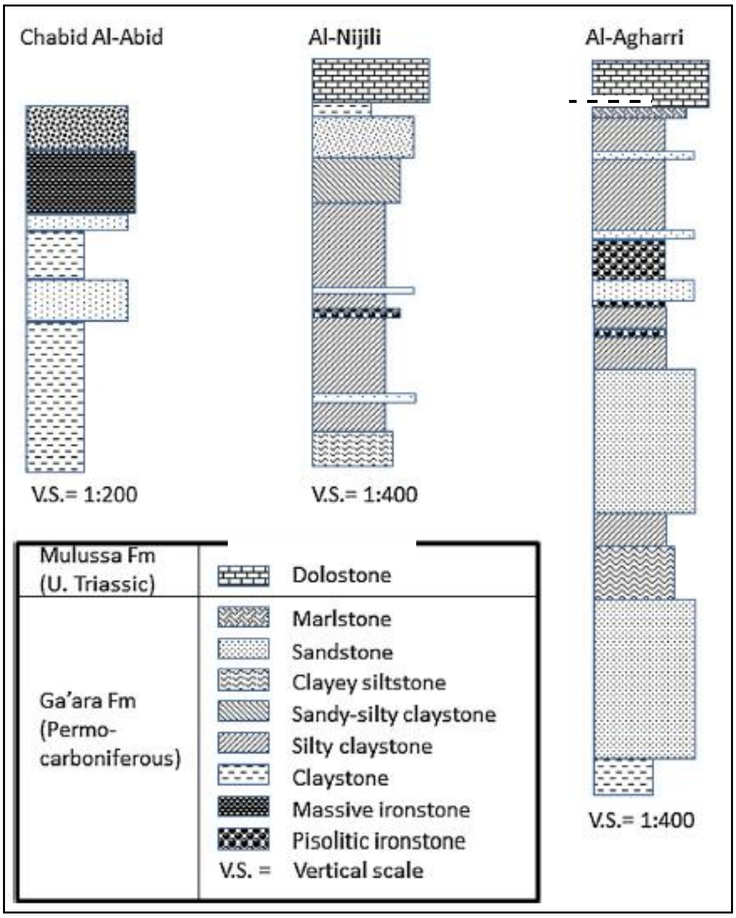

Fig.2: Selected columnar sections of the upper part of Ga'ara Formation in Chabid Al-Abid at the western rim, and Al-Nijili and Al-Agharri at the southern rim of the Ga'ara depression (Tobia *et al*., 2014)

The thickness of the clastic unit increases from south to north at the expense of the carbonate unit. The total thickness of the formation is 40 – 70 m; the clastic unit varies in thickness from about 15 m in the south to about 50 m in the north. The clastics of the Hussainiyat Formation are underlain by a deeply weathered and karstified surface of the Ubaid carbonates (Fig.3). The contact is marked by a reddish or yellowish brown uneven surface, generally inclined towards the east. In the south, the surface of the Ubaid Formation is overlain by up to 5 m thick white to purple mottled kaolinitic claystone that occasionally contains goethite concretions, rare iron pisolites and common fossil rootlets. In the north this claystone is black with pyrite crystals and pyrite concretions. The kaolinitic claystone is sharply overlain in the south by a remarkable horizon of green and brown pisolitic-colloform ironstone, up to 2.5 m thick, which is devoid of clastic material and resembles an in situ (undisturbed), indurated ferricrete horizon. This horizon is cut at various levels by lenses of sandy and poorly-sorted fragmentary ironstone, comprising a heterogonous mixture of rounded quartz sand, ironstone intraclasts and kaolinitic breccia.

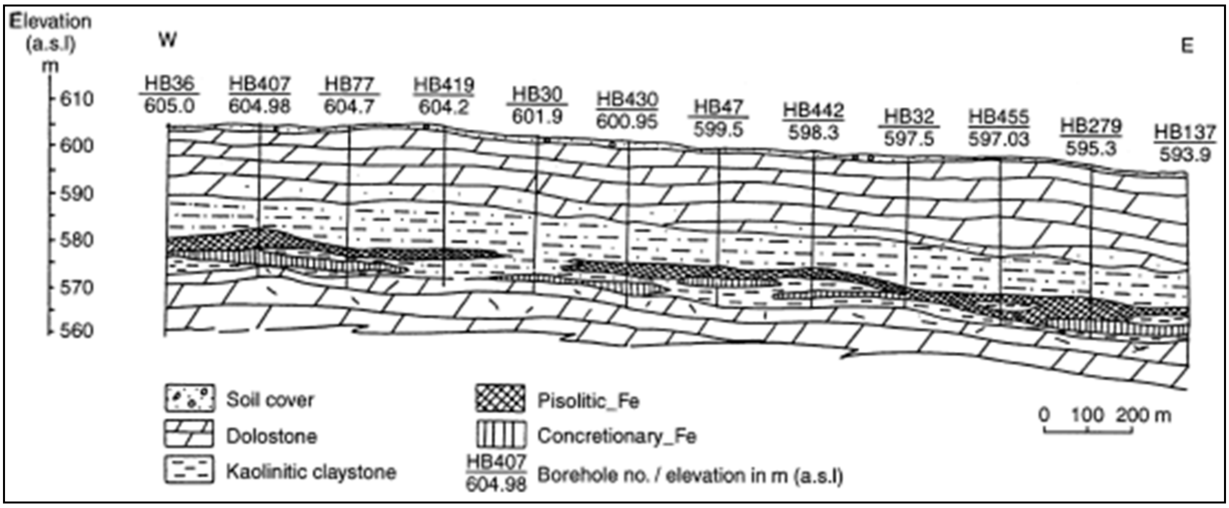

Fig.3: Geological cross section of the ironstone-bearing sequence northeast of Rutba Town (Al-Bassam and Tamar-Agha, 1998)

PETROGRAPHY AND MINERALOGY OF THE IRONSTONES

- **The Ga'ara Deposit.**

Two types of ironstone are recognized based on field observations and microscopic studies; massive ironstone and pisolitic-oolitic ironstone (Figs.4 and 5), both of which occur as thin and lenticular beds. The pisolitic-oolitic ironstones are restricted to the southern rim of the Ga'ara depression, forming up to three horizons in some localities. The pisolitic ironstone are sometimes associated with crust few centimetres to a couple of decimeters thick (Figs.6 and 7a,b) The massive ironstone is found as lenses of limited thickness and extension; the thickness ranges from few centimeters up to ~4 m.

– **Massive ironstone:** Two varieties of massive ironstone are recognized; sandy and clayey (Figs.4a, c, d, 5a – d and 8a). The former consists of subangular to subrounded quartz grains, fine silt to coarse sand in size, cemented by colloform, botryoidal hematite and goethite (Figs.5, 7c, d and 8). The quartz grains commonly show corroded outlines (Fig.7e). The color of these rocks varies from dark reddish brown to yellowish brown depending on the content, type and ratio of the iron minerals. Microscopic study indicates that the iron oxyhydroxides were deposited as colloids around quartz grains as an open space filling from gel-like solutions. Hematite is the predominant mineral with lesser amounts of goethite . Kaolinite and quartz are the major non-ferruginous minerals in this type of ironstone; secondary calcite occurs as crack-filling. Goethite is the precursor mineral grown and crystallized to fibrous crystals with continuous growth it produced an interference surface (Figs.4e and 7e), one of the features that indicates the deposition from colloidal solution (Stanton, 1964; Misra, 1999). The clayey massive ironstone consists of clay within the mixed hematite-goethite bearing kaolinitic mudstone. The size of the pellets is between (0.5 and 2.1) mm. This type of ironstone has a wide range of hardness, depending on the clay content and the intensity of weathering. The most common colloidal texture of goethite is botryoidal with syneresis cracks (Fig.7f).

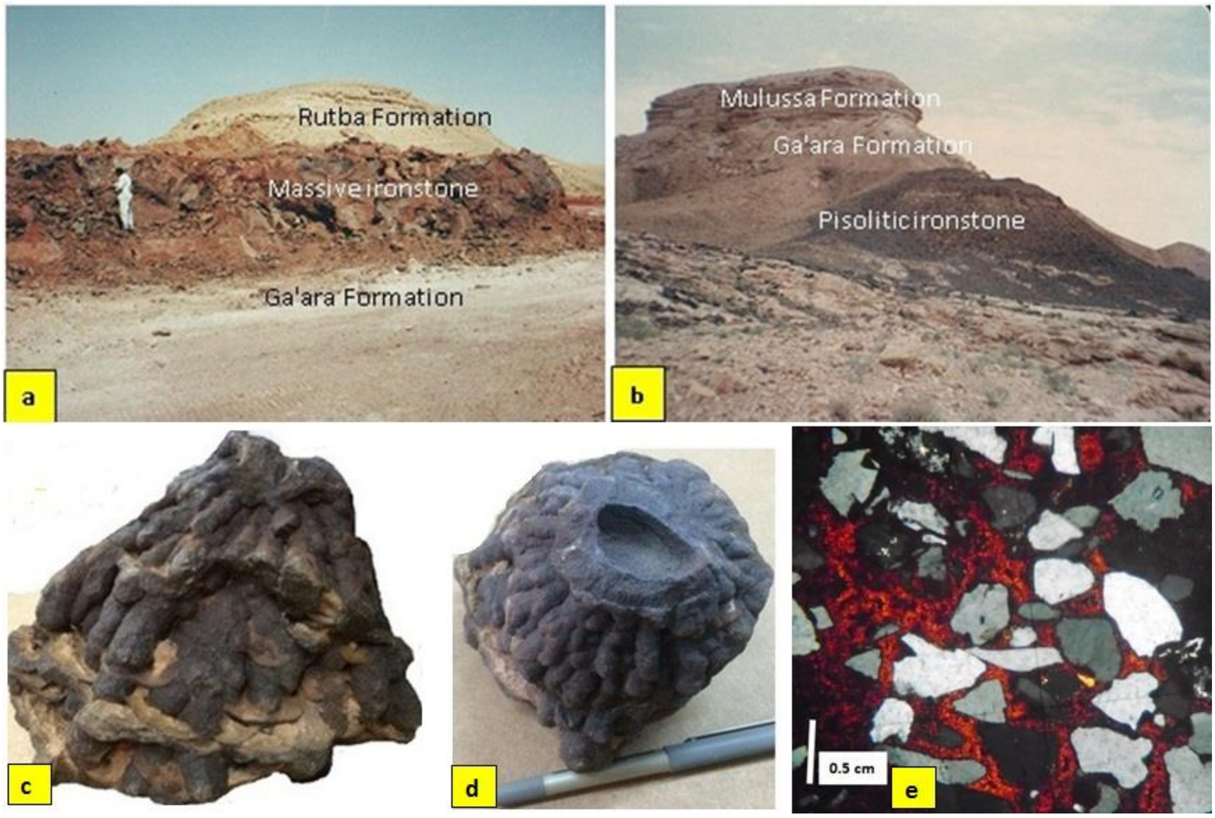

Fig.4: Massive and pisolitic ironstones

a) Thick massive ironstone of ferruginous and cross-bedded sandstone from Chabid Al-Abid locality at the western rim of the Ga'ara Depression. **b)** Thick pisolitic ironstone. **c)** Ferruginous sandstone from the massive ferruginous sandstone of Chabid Al-Abid locality. **d)** Same sample with different view. **e)** Photomicrograph of the same sample showing quartz grains surrounded and partially or wholy replaced by hematite and goethite as hematite replacing and engulfing quartz grains

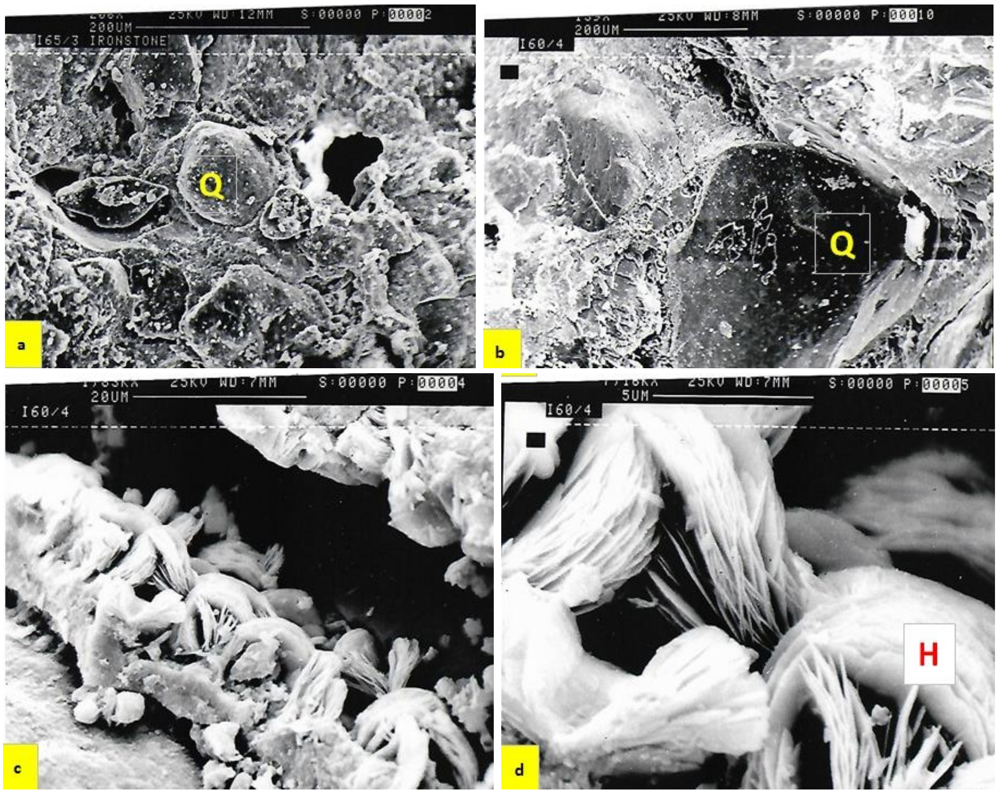

Fig.5: SEM photomicrographs of massive ferruginous sandstone at Chabid Al-Abid locality (same sample in Figs.4c, d and e). Q-quartz grain, H-hematite cement. Hematite cement fill the pore spaces and surrounds the quartz grain which indicate replacive nature

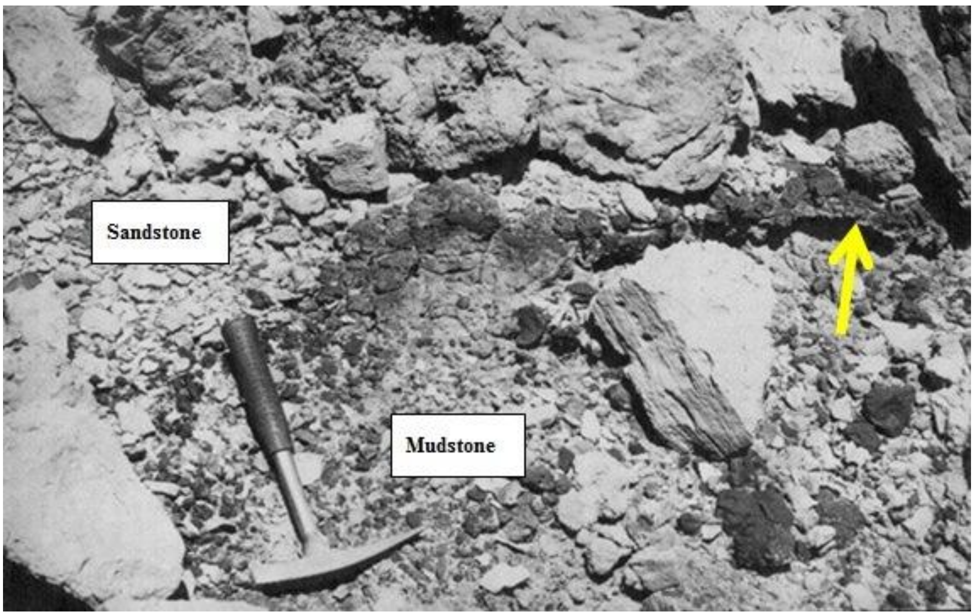

Fig.6: Crust of iron oxyhydroxides on top of a mudstone layer separating the overlying sandstone bed. The crust is irregular but mostly domal and indicates a ferricrete origin. Arrow points to the crust, Wadi Al-Agharri, southern rim of the Ga'ara Depression

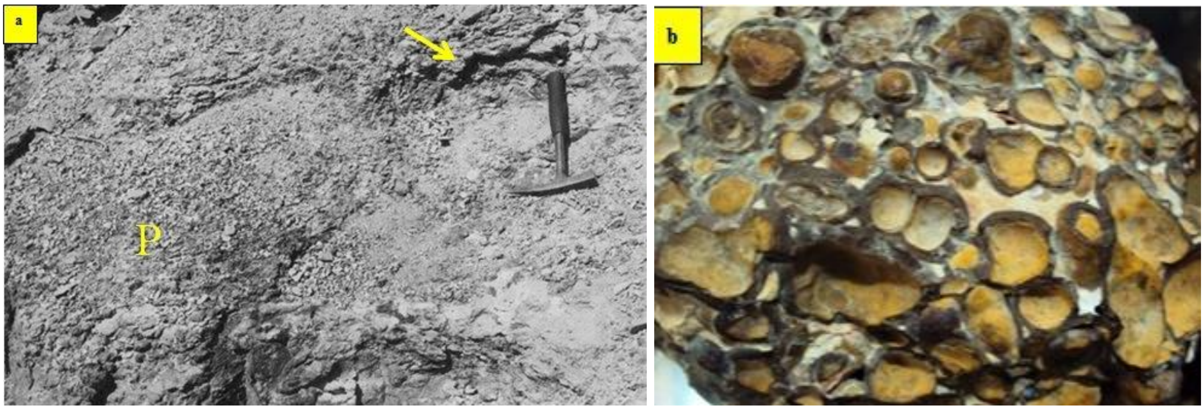

Fig.7: **a)** Pisolitic iron (P) overlain by a crust at wadi Al-Agharri, southern rim of the Ga'ara Depression. **b)** Details of crowded pisolites with minimal matrix

– **Pisolitic-oolitic and concretionary ironstones:** These types of ironstones are restricted to the southern rim of the Ga'ara Depression, forming lenses in more than one level (Fig. 2). There is up to three lenses in several localities with no obvious correlation between these lenses in the neighboring outcrops. Iron pisolites and/or concretion are the characteristic textural feature in this type of ironstone (Figs.5 and 7). The ironstone lenses vary in thickness from several centimeters up to ~2 m. The pisolites are both solitary and intact, 'floating' in kaolinitic mudstone matrix, or crowded with minimal matrix. Plant debris, roots and rootlets are also common features in the mudstone but they are inversely proportional with the pisolites and the concretions. Other pisolites are broken and fragmentary, i.e., reworked and found associated with other intraclast and extraclasts of the lag deposits, at the base of the channeled sandstone. Some of the broken and fragmentary pisolites act as nuclei for larger compound pisolites (Figs.8 and 9) and suggests that such pisolite debris have suffered syndepositional reworking. The pisolites are yellowish to brownish yellow in color, formed of numerous concentric coats (cortices) nucleated around quartz grains, yellow limonitic-clay fragments and earlier pisolite fragments (Fig.9a). There are large composite pisolites containing several smaller pisolites and oolites which have acted as a nucleus. The cortices are nearly symmetrical in thickness (Fig.9b), depicting the outer shape of the nucleus in the internal cortex, but tending to be sub-spherical to spherical and of a diameter between 2 mm and 13 mm. The pisolites are usually floating in ferruginous mud representing ~70% of the sample in some lenses such as in Al-Agharri and Mulussa localities. Radial and concentric cracks are common in these pisolites (Fig.9c).

X-ray diffractometry revealed that goethite and kaolinite are the most dominant minerals in the pisolites, whereas goethite, hematite and quartz or kaolinite are dominant in the massive ironstone. Minor amounts of secondary gypsum are recorded in some samples. Petrographic studies show a kaolinite thin layer alternating goethite (Fig.9d) with sheaths of hematite; the latter produced by dehydration of goethite. There is more than one stage of cortices growth, which can be distinguished by the color variation or by concentric cracks that are filled by secondary gypsum or calcite. The mineralogical composition of the matrix is goethite and kaolinite with minor amount of hematite. This texture indicates open space filling deposition and colloidal nature of the solution.

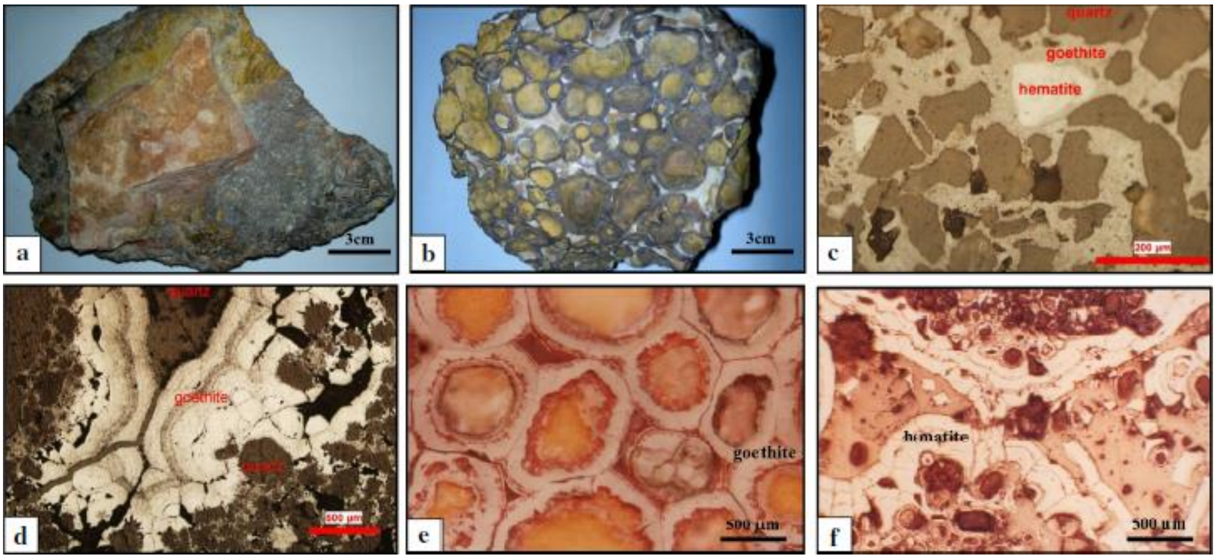

Fig.8: **a)** Hand specimen of massive ironstone at Umm Idaya section, southern rim **b)** Hand specimen of pisolitic-oolitic ironstone, Al-Nijili section, southern rim; **c)** Subangular to subrounded quartz grains cemented by goethite which contains hematite grains (sandy ironstone); **d)** Colloform texture, produced by deposition from colloidal solution as open space filling; **e)** Interference surfaces due to the continuous growth of the goethite crystals; **f)** Syneresis cracks due to conversion of goethite to hematite (Tobia *et al*., 2014)

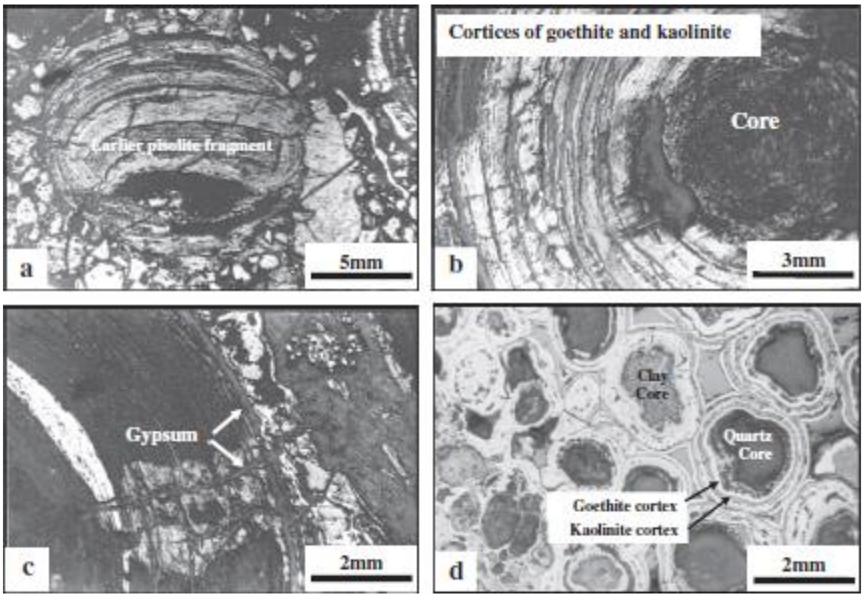

Fig.9: **a)** Concentric coats (cortices) around earlier pisolite fragment; **b)** Nearly symmetrical cortices in thickness depicting the outer shape of nucleolus; **c)** radial and concentric cracks in pisolite filled by gypsum; **d)** Alternation of kaolinite and goethite layers (Tobia *et al*., 2014)

- **The Hussainiyat Deposit**

Facies analysis by Al-Bassam and Tamar-Agha (1998) revealed three main lithofacies in the Clastic Unit of the Hussainiyat Formation: **A.** Sandstone, **B.** Mudstone and **C.** Ironstone, each of which is subdivided into several sublithofacies. The ironstone is divided into four sublithofacies: C1) Autochthonus Pisolitic-Colloform Ironstone; C2) Intraclastic Ironstone; C3) Massive Sandstone-Ironstone and C4) Concretionary Ironstone. The pisolitic ironstone is the most common component of the Hussainiyat ironstone deposit, followed by massive sandy ironstone, fragmentary intraclastic ironstone and concretionary ironstone (Figs.10a – f).

The iron pisolites are brown or green in color, formed of numerous concentric coats surrounding a nucleus of quartz, mud clasts, fossil wood fragment or pisolite fragment. The coats are mostly symmetrical in thickness (Fig.11a) depicting the outer shape of the nucleus in the internal coats, but tending to be spherical in the outer coats. Radial and concentric cracks are common in these pisolites (Fig.11b and c). Concentric cracks are usually associated with hematite. Iron oolites are of the same composition and structure as the iron pisolites, but of smaller size (less than 2 mm in diameter). On few occasions multiple iron pisolites are combined together within an outer coat. Two types of pisolites are recognized on the basis of mineral composition (Al-Bassam and Tamar-Agha, 1998). These are goethite-quartz (Si-type) and goethite-kaolinite (Al-type); the latter is the most common. In these pisolites thicker goethitic laminae alternate with thinner kaolinitic laminae (Fig.11a). In the Si-type pisolite a small amount of detrital quartz is observed at the contact between goethitic and kaolinitic laminae. Colloform iron is commonly found together with the pisolitic-oolitic iron. It is green or brown in color, laminated and consanguineous with the pisolitic material in all respects, except the shape. The sandy ironstone consists of angular to sub-rounded quartz grains, 0.1 – 0.5 mm in diameter, cemented by goethite of colloform texture. Hematite is present in minor amounts as pseudomorphic flat crystals on the goethite (Fig.11d and e). The quartz grains commonly show corroded boundaries (Fig.11f). The intraclastic iron components range from 0.2 to 2 cm in size, poorly sorted and angular to subangular. These components are associated with subangular fragments of white kaolinitic mudstone of the same size range and coarse to fine sand grains. The fragments are cemented by ferruginous kaolinitic clay. The composition of these intraclasts is similar to their parental material, which is goethite and to a lesser extent hematite.

Quartz is the most abundant detrital component, forming at least 98% of the framework constituents in the sandstones, which are almost matrix-free, hence can be referred to as quartz arenite. The framework fragments are poorly cemented, ranging from poorly to very poorly sorted, and subrounded to subangular. Heavy mineral analysis of 12 selected sandstone samples showed (0.1 – 0.3) wt.% heavy minerals among which opaque are main constituents (40 – 82) % being mostly goethite, hematite and chromite. Zircon, tourmaline and rutile (ZTR) are common (15 – 25) % with minor apatite, pyroxene, hornblende, epidote and staurolite (Al-Bassam and Tamar Agha, 1998).

X-ray diffractometry showed that in the ironstone, goethite is the predominant mineral amongst iron oxyhydroxides; hematite is present, but in small amounts. Disordered kaolinite and quartz are the major non-ferruginous minerals present in the ironstones. Secondary calcite occasionally occurs as crack filling. In the mudstone, kaolinite is the most dominant clay mineral. Minor amounts of mixed-layer illite-smectite, palygorskite and halloysite were also encountered, besides kaolinite, in the upper mudstone horizon only. Quartz and iron oxyhydroxides are the major non-clay minerals in these mudstones. Minor amount of anatase, gibbsite and boehmite were also recorded (Jassim *et al*., 1981; Al-Bassam and Jassim, 1983). The kaolinite is generally disordered, with higher disorder in the reddish brown mudstone than in the white and purple mudstone.

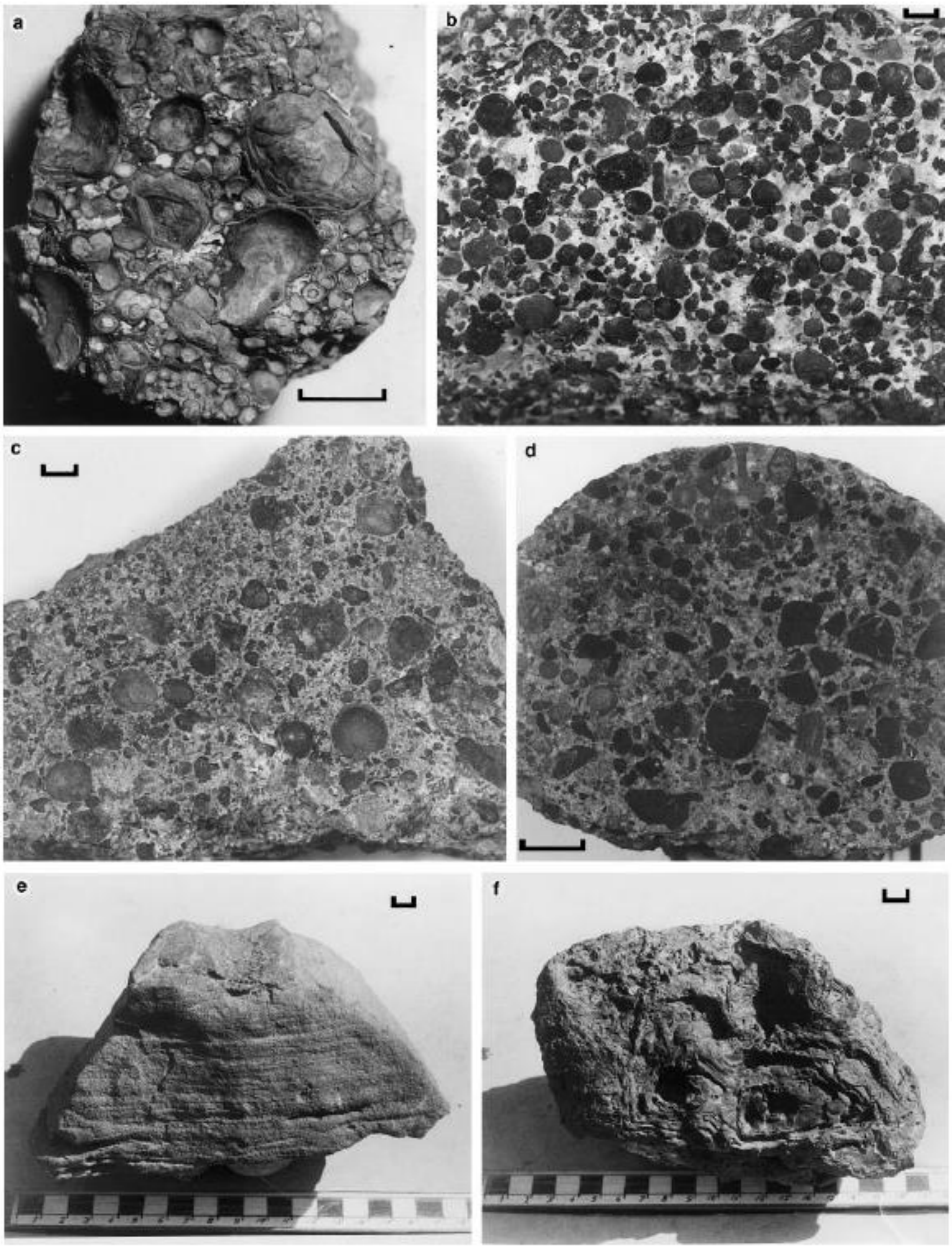

Fig.10: Ironstone textural types in the Hussainiyat Deposit (bar = 1 cm); **a)** Pisolitic-colloform ironstone (sublithofacies C1); **b)** Intraclastic ironstone (sublithofacies C2) iron pisolites in a kaolin matrix; **c)** Intraclastic ironstone (C2) showing iron pisolites in a carbonate-cemented sand matrix; **d)** Intraclastic ironstone (C2) comprised of fragmentary ironstone in a carbonate-cemented sand matrix; **e)** Massive sandstone-ironstone (C3) and **f)** Concretionary ironstone (C4) (Al-Bassam and Tamar-Agha, 1998)

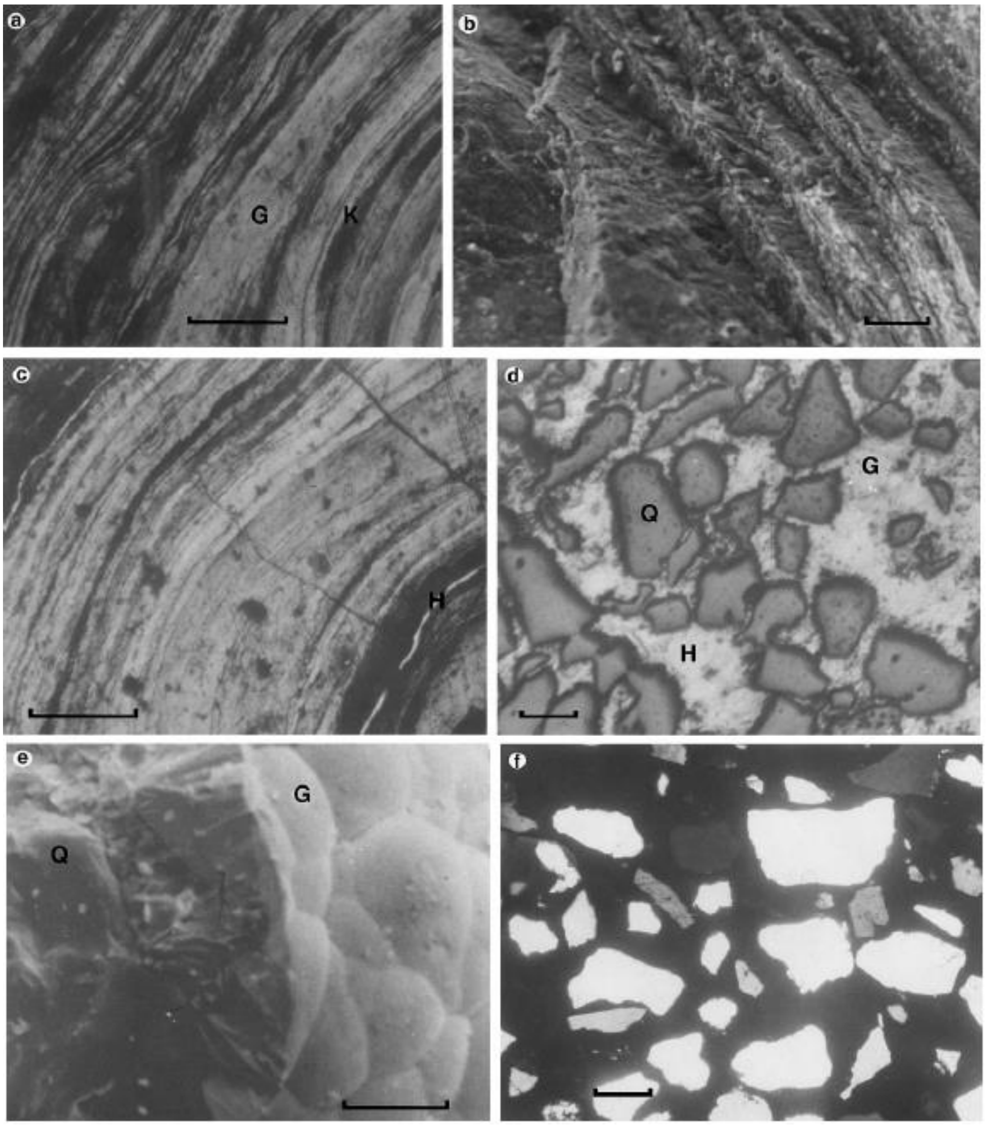

Fig.11: Ironstone microtextures (bar = 0.2 mm); **a)** Goethite (G) and kaolinite (K) laminations in the iron pisolites (reflected light); **b)** Accretion coats in the iron pisolites (scanning electron microscope photomicrograph); **c)** Radial cracks and concentric cracks, associated with hematite (H) in the iron pisolites (reflected light); **d)** Sandy ironstone comprised of quartz grains (Q), goethite cement (G) and hematite crystals (H) (reflected light); **e)** Sandy ironstone showing colloform texture of the goethite cement (G) around quartz grains (Q) (scanning electron microscope photomicrograph); **f)** Sandy ironstone showing corroded quartz grains cemented by goethite (black) (transmitted light, crossed nicols) (Al-Bassam and Tamar-Agha, 1998)

GEOCHEMISTRY OF THE IRONSTONES

- **The Ga'ara Ironstone Deposit**

A statistical summary of major and trace elements chemical analysis of 32 ironstone samples from the Ga'ara ironstones is presented in Table (1). The chemical composition of these samples mainly consists of SiO_2, Fe_2O_3 and Al_2O_3, which represent 80% of all ironstones constituents and correspond to goethite, hematite, kaolinite, and quartz. The average content of Fe_2O_3 in the matrix of the pisolitic ironstone and that of the massive ironstone varies between (7.01% and 83.7 %), respectively. This variation is also shown in other major elements following variation in rocks mineralogy, especially in the contents of hematite, goethite, kaolinite, quartz, and carbonate. Matrix with higher Si contents tends to have higher Al content which indicates excess kaolinite content.

The pisolitic ironstone has higher Fe and lower Si contents, whereas, the massive ironstone has higher (Ca + Mg) and lower Al contents. The chemical analyses of the pisolites and matrix generally show similar behavior, both are enriched in V, Cr, Ni, As, Y, Zr, W, and Nb; and are depleted in P, Zn, Mo, and Ba (Table 1). The Cr and V are associated with Fe because of their similar geochemical behavior in the sedimentary environment (Boulange *et al*., 1990). The relatively high Cr/Ni ratio in the pisolite and matrix is due to the association of Cr with kaolinite, supported by the positive correlation between Al_2O_3 and Cr in the pisolites and its matrix (r = 0.57 and 0.70 respectively). In comparison with the trace element concentrations of the continental earth crust given by Rudnick and Gao (2003), the Ga'ara massive ironstone is relatively enriched in V, Ni, As, Zr, Nb, Co, W, and Mo; and depleted in P, Li, Cr, Cu, Zn, Y, La, Ce, and Ba; while Mn is almost the same. The Cr/Ni, Co/Ni and Mn/Fe ratios are lower in the Ga'ara ironstone compared to that of the Earth's continental crust (Table 1).

Table 1: Chemical composition of the Ga'ara ironstones compared to the composition of the Earth's continental crust (Tobia *et al*., 2014)

Oxides (wt. %) Elements (ppm)	Massive ironstone		Pisolites		Matrix		Continental crust*
	Range	Average	Range	Average	Range	Average	
Fe_2O_3	41.22 – 83.7	59.94	13.5 – 68.0	55.74	7.01 – 46.8	20.90	5.04
MnO	0.01 – 030	0.12	0.01 – 0.77	0.29	0.01 – 0.39	0.09	0.10
CaO	0.08 – 20.0	3.73	0.24 – 1.99	0.85	0.04 – 5.97	1.39	3.59
K_2O	0.01 – 0.08	0.04	0.01 – 0.08	0.02	0.01 – 0.40	0.06	2.80
SiO_2	5.5 – 51.91	29.24	9.07 – 48.1	20.80	29.54 – 80.5	51.18	66.6
Al_2O_3	0.40 – 2.50	0.99	5.20 – 25.39	10.52	9.01 – 23.27	15.82	15.4
MgO	0.01 – 0.52	0.15	0.01 – 0.37	0.20	0.01 – 0.30	0.08	2.48
Na_2O	0.01 – 1.25	0.37	0.01 – 1.16	0.44	0.01 – 0.93	0.33	3.27
L.O.I	1.17 – 9.88	5.38	8.51 – 12.37	10.52	3.12 – 11.29	8.12	–
P	77 – 152	120	104 – 277	152	62 – 227	125	654
Li	2 – 6	3	9 – 43	27	10 – 91	69	24
V	38 – 877	442	426 – 1197	734	80 – 929	378	97
Cr	n.d. – 111	52	45 – 373	178	58 – 227	148	92
Co	n.d. – 32	25	n.d. – 42	28	n.d. – 31	–	17.3
Ni	65 – 265	140	110 – 237	177	68 – 284	142	47
Cu	5 – 30	10	11 – 159	24	2 – 28	14	28
Zn	n.d. – 36	28	12 – 28	21	16 – 27	21	67
As	n.d. – 65	25	n.d. – 133	90	n.d. – 195	76	4.8
Y	7 – 20	16	24 – 59	42	26 – 69	41	21
Nb	6 – 27	15	8 – 47	30	20 – 64	43	12
Mo	n.d. – 37	20	n.d. – 22	–	n.d. – 2	–	1.1
Ba	16 – 208	60	12 – 88	28	19 – 55	34	628
La	3 – 36	13	3 – 101	30	2 – 138	44	31
Ce	4 – 72	27	n.d. – 387	58	n.d. – 709	33	63
W	n.d. – 39	9	6 – 60	25	21 – 82	45	1.9
Bi	n.d. – 22	–	n.d. – 18	–	n.d. – 29	18	–
Zr	560 – 1265	766	183 – 890	542	481 – 1276	830	193
Cr/Ni	0.00 – 1.37	0.365	0.31 – 2.29	1.044	0.504 – 1.99	1.195	1.96
Co/Ni	0.00 – 0.16	0.036	0.00 – 0.20	0.084	13 – 1078	0.055	0.37
Mn/Fe	0.0003 – 0.01	0.0009	0.00074 – 0.033	0.0043	0.0009 – 0.077	0.003	0.022

* After Rudnick and Gao (2003)

- **The Hussainiyat Ironstone Deposit**

The chemical composition and geochemical characteristics of the ironstones and associated kaolinitic mudstones were studied by Al-Bassam and Tamar-Agha (1998) through 76 samples collected from one of the best developed ironstone-bearing sections (Borehole HB 149). In addition, about 20 samples of main ironstone textural types were also analyzed (Tables 2 and 3). The results of chemical analyses reflect sedimentary rocks of high maturity, where SiO_2, Al_2O_3, Fe_2O_3 and TiO_2 comprise more than 85% of the chemical constituents. These oxides are controlled by kaolinite (SiO_2, Al_2O_3), goethite and hematite (Fe_2O_3), quartz (SiO_2) and anatase (TiO_2).

The chemical analyses of the samples collected from borehole HB 149 revealed distinct geochemical facies that correspond well with lithology (Fig.12). The basal kaolinitic claystone (sublithofacies B2) and upper kaolinitic mudstone (sublithofacies B3) are generally similar, being high in alumina and silica, and low in iron. However, the Al_2O_3/ SiO_2 ratio in the basal claystone corresponds to kaolinite composition, whereas this ratio is lower in the upper mudstone and indicates about 20% of free silica (quartz). The undisturbed pisolitic-colloform ironstone (sublithofacies Cl) is high in iron, but low in silica and alumina. In this ironstone, the Al_2O_3/ SiO_2 ratio corresponds to kaolinite composition, but it is depleted in silica relative to iron and alumina. The SiO_2/ (Al_2O_3 + Fe_2O_3) is about 0.3 in the ironstone (Cl) compared to 0.8 and 1.3 in the lower (B2) and upper (B3) mudstones respectively. On the other hand, the reworked intraclastic ironstones (sublithofacies C2) are high in iron and silica, but low in alumina. The Al_2O_3/SiO_2 ratio indicates about 25% of free silica (quartz) present at the expense of kaolinite. Chromium content is high relative to other trace elements in the Hussainiyat Deposit. It is particularly enriched in the Si-type iron components, and highly depleted in the iron concentrations. The high Cr content resembles that usually found in soils developed from basic and intermediate igneous rocks (Aubert and Pinta, 1977), and reflects Cr concentration with the residual elements upon lateritization and during pedogenesis. Whereas, the low Cr content of the concretions resembles that usually found in bog iron ores (Rankama and Sahama, 1950). Both goethite and kaolinite can serve as host minerals for Cr. The Cr/Ni ratio in the ironstones is high and variable (1.5 – 7.5) except in the iron concretions where it is too low (0.1).

In comparison with the Earth's continental crust (Ronov and Yaroshevsky, 1969 and 1972), the Hussainiyat ironstones and mudstones are relatively enriched in Fe, Ti, Ni, Co, Cr, Ga, Pb and U, and are depleted in Si, Ca, Mg, Na, K, Mn, Zn, Cu, Rb and Sr. Levels of Al and P are about the same as in average continental crust. Uranium is enriched several times in the Hussainiyat ironstones relative to its average concentration in the Earth’s continental crust; up to 35 ppm U was recorded in the Al-type pisolites, reflecting uranium retention in the resistates under oxidizing conditions. However, radiometric analysis showed significant disequilibrium in uranium and its daughters, suggesting long exposure under weathering conditions. Some bauxites are known with high uranium concentrations (Rogers and Adams 1969), and most laterites are radioactive. Uranium may be trapped in oxidizing environment as UO_4^{-2} in ferric hydroxide colloids, which are positively charged and can absorb anionic groups.

Cobalt and nickel are the group of elements enriched in the Hussainiyat Deposit, especially in the concretionary ironstone. These two elements occur together with Fe in parent rocks (Mason, 1966). Iron is more easily oxidized to Fe^{+3} and readily precipitates, whereas Co and Ni require higher oxidation potentials. The Co/Ni ratio in the Hussainiyat ironstones is about 0.5 in all types**,** which is close to that usually found in basic and intermediate igneous rocks (Rankama and Sahama, 1950). Manganese is depleted in the Hussainiyat deposit (except in iron concretions) relative to the earth's crust and relative to the significant high Fe enrichment in the deposit. It is geochemically linked to Fe in primary rocks, but it seems that supergene processes have resulted in their separation. They are both mobile in reducing environment, but Mn requires a higher oxidation potential than Fe^{2+} to precipitate (Mason, 1966). Copper content is higher in the upper mudstone (B3), following K and Mg, which may suggest illite and palygorskite as host minerals. Among the ironstone types, Cu is higher in the concretionary ironstones and in the Si-type ironstones. Rubidium and strontium are also depleted; the former is relatively higher in the upper mudstone (B3) which is explained by the presence of illite. The relative depletion of these elements is due to complete leaching of their host minerals during lateritization and pedogenesis.

Table 2: Chemical composition of the ironstones and mudstones in borehole HB 149, the Hussainiyat Deposit (Al-Bassam and Tamar-Agha, 1998)

wt.%	1	2	3	4	5	6	7
SiO_2	38.10	19.39	40.87	23.59	38.29	48.74	31.98
Al_2O_3	32.59	15.53	12.61	14.74	13.75	23.01	16.29
Fe_2O_3	13.30	51.19	35.52	47.37	38.01	12.81	38.36
P_2O_5	0.16	0.32	0.28	0.27	0.22	0.14	0.33
TiO_2	1.40	0.96	0.78	0.80	0.76	1.23	0.87
CaO	0.20	0.81	0.96	1.26	0.25	0.58	0.59
MgO	0.14	0.17	0.17	0.26	0.14	0.53	0.20
K_2O	0.14	0.12	0.11	019	0.18	0.77	0.16
Na_2O	0.27	0.57	0.32	0.59	0.54	0.57	0.23
H_2O	12.21	10.10	7.17	9.50	6.96	9.99	0.35
ppm	Trace elements						
Mn	61	365	183	324	207	131	410
Ni	120	114	75	77	47	66	180
Cu	3	8	8	27	28	34	40
Zn	23	46	35	48	42	51	70
Rb	10	10	12	10	11	19	11
Sr	89	72	85	55	45	81	65
Pb	32	50	38	48	44	31	40
Wt.%	Mineral analysis based on chemical composition						
Goethite	15	54	37	50	40	14	42
Kaolinite	82.5	39.3	31.9	37.3	34.8	58.3	41
Quartz	0.1	1.3	26.2	6.4	22.3	21.9	13
Others	2.4	5.4	4.9	6.3	2.9	5.8	4

1) Sublithofacies B2 at (31.5 – 34.5) m (13 samples); **2)** Sublithofacies C1 at (30.5 – 31.5) m (5 samples); **3)** Sublithofacies C2 at (28.7 – 30.5) m (8 samples); **4)** Sublithofacies C1 at (26.1 – 28.7) m (12 samples), **5)** Sublithofacies C2 at (24.0 – 26.1) m (11 samples), **6)** Sublithofacies B3 at (18.5 – 24.0) m (27 samples), **7)** Average Hussainiyat ironstone deposit (Etabi and Dimitrov, 1982).

Table 3: Chemical and mineralogical composition of individual textural types of ironstones (Al-Bassam and Tamar-Agha, 1998)

Wt.%	**Al-types**			**Si-types**			**Concretions**
	1	**2**	**3**	**4**	**5**	**6**	
SiO_2	13.41	19.34	9.16	26.98	43.96	49.97	1.43
Al_2O_3	13.22	16.33	8.78	4.06	3.88	2.42	0.52
Fe_2O_3	58.53	52.53	69.16	57.80	41.14	40.21	84.50
TiO_2	0.14	0.86	0.50	0.71	0.66	0.51	0.05
H_2O	12.12	8.02	1054	8.90	8.16	6.26	8.89
ppm	Trace elements						
Mn	300	520	560	241	175	200	1500
Co	80	70	100	91	89	40	120
Ni	180	110	200	174	160	100	316
Cu	12	11	17	64	86	50	124
Zn	28	52	70	40	35	45	55
Cr	530	325	300	819	801	750	30
Ga	330	300	150	150	100	100	38
U	35	22	18	25	20	8	19
Wt.%	Mineral analysis based on chemical composition						
Geothite	64	58	76	64	45	44	93
Kaolinite	30	41	20	11	10	6	1
Quartz	-	-	-	22	40	47	1
Gibbsite[a]	3	-	2	-	-	-	-
Others	3	1	2	3	5	3	5

1) Pisolites; **2)** Colloform ironstones; **3)** Structureless intraclasts.

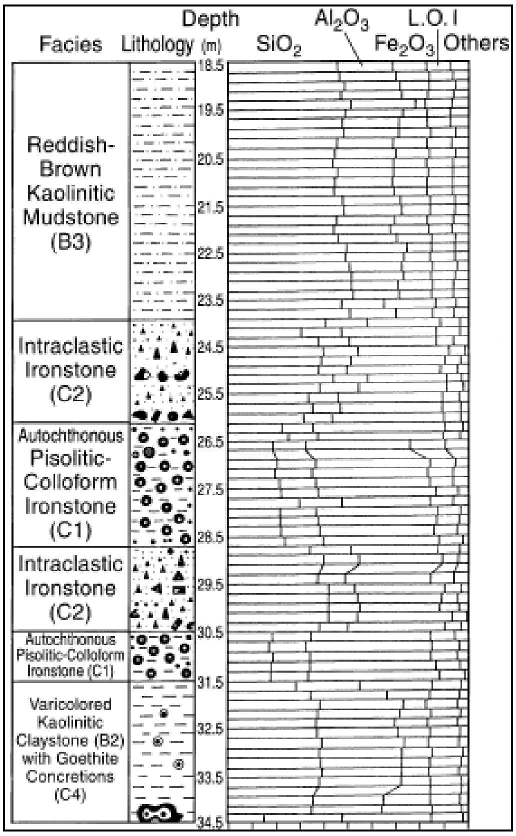

Fig.12: Distribution of major chemical constituents against lithological sequence in borehole no. HB 149, the Hussainiyat deposit (sampling interval 0.2 m) (Al-Bassam and Tamar-Agha, 1998)

GENESIS OF THE IRONSTONES

- **The Ga'ara deposits**

The Ga'ara ironstones are of two different textures and origins, namely the pisolitic and concretionary (crust), and massive ironstone. The pisolitic and the concretionary ironstones are of pedogenic origin (Tamar-Agha, 1986 and 1993) affecting the floodplain deposits, i.e. syndepositional, whereas the massive ironstone is early diagenetic. The Ga'ara deposits originated from highly weathered (under humid and tropical climate) plutonic igneous and metamorphic rock complexes and older sedimentary rocks, from the Arabian Shield, (Tamar-Agha, 1986 and 1993; Tobia *et al.*, 2014). The detritus were brought from the source area to the depositional site by streams. The fluvial system in the depositional site represents meandering-river system comprising active channels and overbank deposits represented by wide floodplains, lakes and swamps (Tamar-Agha, 1986). Most of the iron oxyhydroxides were transported from the source area as coatings on the clay particles. Several studies demonstrated that the iron oxyhydroxides in the kaolinitic-clay deposits are fine particles coating the kaolinite grains for the difference in charges between them (Ibanga *et al*., 1983; Watanaba, 1987; Al-Youzbagy, 1989).

Tamar-Agha (1986 and 1993) believed that the iron pisolites and concretions grew first in the soils of the floodplains by pedogenic processes in what is known as ferricretes. They are mostly formed from colloids. The colloidal state is concluded from their textures and microtextures such as the solitary distribution in the mudstones, colloform texture and concentric accretionary coats, interference surfaces due to the continuous growth of the goethite crystals and syneresis cracks (Figs.7a-f). The massive ironstone is diagenetic by several mechanisms such as Fe-oxyhydroxide cement growth in the voids and spaces and/ or replacement of precursor sand grains or cement such as the poikilotopic calcite cement (Fig.4); or by oxidation of pre-existing sulphides (such as pyrites which grew along roots, rootlets and other plant remains (Tamar-Agha, 1986, 1993).

The low concentration of Mn in the Ga'ara ironstone indicates deposition from fresh water (Canavan *et al*., 2007; Rigaud *et al*., 2013). The Mn/Fe ratio (Table 1) is low which reflects the high separation between the two elements in the hydromorphic environment. They are both mobile in reducing conditions, but Mn requires higher oxidation potential to precipitate than Fe^{2+} (Canavan *et al*., 2007). The high Cr content resembles that usually found in soils developed from mafic and intermediate igneous rocks (Aubert and Pinta, 1977), and reflects Cr concentration with the residual elements upon lateritization and during pedogenesis. Whereas the low Cr content (as in massive ironstone) resembles that usually found in bog iron ores (Rankama and Sahama, 1950). Tobia *et al*. (2016) believe that the mineralogical results suggest that lateritization have had minor role in the development of the Ga'ara ironstone deposits, suggested by the low Al-substitution for Fe in the Fe-oxyhydroxide minerals, reaching a maximum of 8% moles AlO (OH) in the goethite of iron pisolites and less than that in the associated goethite. Free alumina was detected only in one pisolite sample collected from the pisolitic ironstone lenses at the unconformable contact with the overlying Mulussa Formation (Triassic) at Al-Nijili locality (Fig.1).

- **The Hussainiyat deposit**

The provenance of the clastics of the Hussainiyat Formation is discussed by Al-Bassam and Tamar-Agha (1998). They suggest that the clastics were derived from older lateritized rocks and transported by rivers to the depositional site. A variety of igneous, metamorphic and sedimentary rocks could have contributed and served as source rocks for the Hussainiyat clastics. The nature of the composite grains, strained quartz, arrangement of inclusions and the presence of some diagnostic heavy minerals indicate low and medium grade metamorphic sources; whereas, clean quartz and high ZTR ratio indicate reworked older sedimentary clastics. The mixing of iron oxyhydroxides with kaolinite may reflect an originally iron-rich mother rock, enhanced by lateritization in the source area. Intermediate and basic igneous rocks might have some contribution to the iron enrichment in the source area in view of the relatively high Co, Ni and Cr contents, and the high Co/Ni and Cr/Ni ratios in the ironstones. The parent rocks were deeply weathered in situ sometime in the Late Triassic and Early Jurassic, under a humid and hot tropical climate favorable for laterite formation. This tropical weathering is reflected by the underlying deeply weathered and highly karstified Ubaid Formation (Liassic), and overwhelming presence of kaolinite and residual elements (Fe, Al and Ti). The source rocks may have formed part of the rock complexes of the Arabian Shield that were exposed to in situ lateritization at that time. The lateritic products (Fe-oxyhydroxides and kaolinite) were later transported, together with quartz, by rivers from the source area to the depositional site (Fig.13). Iron was transported from the source area mainly as ferric oxide coatings on kaolinite particles and possibly also in colloidal suspension. The transported materials were sorted upon deposition in various fluviatile sedimentary environments and were subjected to several intervals of exposure and pedogenesis.

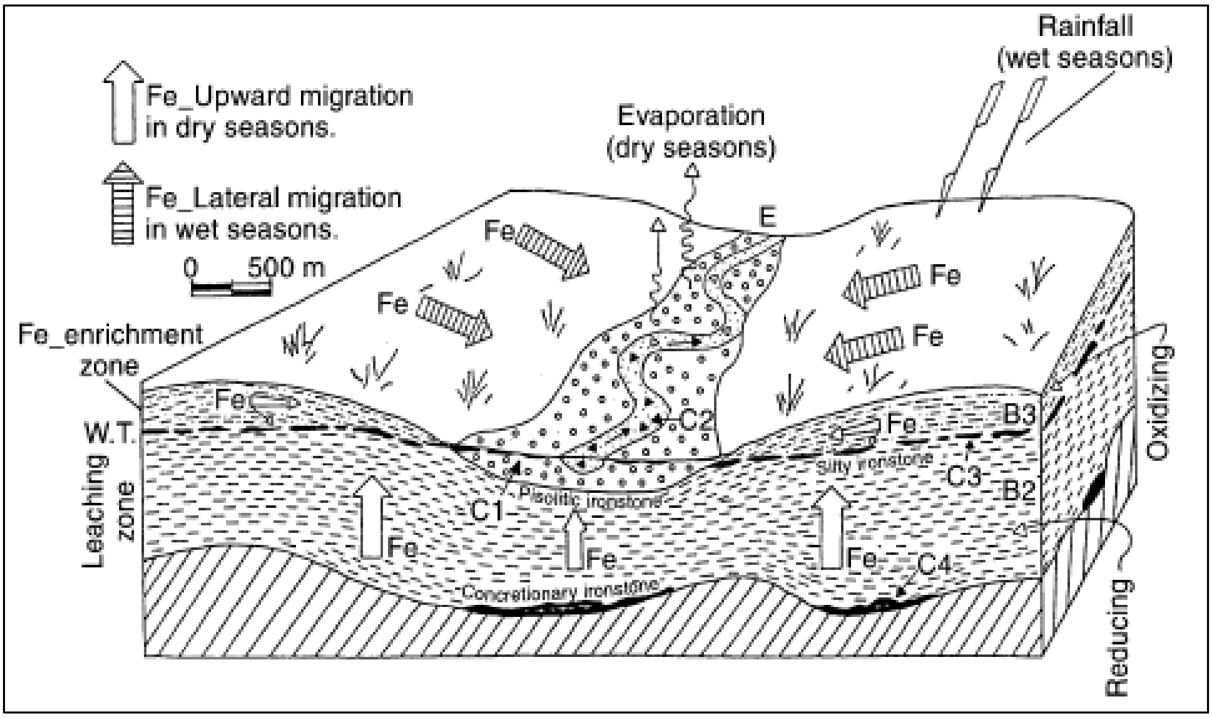

Fig.13: Depositional systems of the Hussainiyat ironstone deposit
(Al-Bassam and Tamar-Agha, 1998)

Two different facies associations are recognized by Al-Bassam and Tamar-Agha (1998); fining-upward sequences in the northern zone representing meandering rivers and mudstone-ironstone in the southern zone representing floodplains occasionally dissected by wadis. Quartzose sandstones were deposited in active channels and Fe-rich kaolinitic mudstones were deposited in swamps and overbanks. Iron concretions grew in the swamp and marsh environments and were embedded in kaolinitic mudstone. They are goethitic at the present time, but their original composition is controversial. Their low Cr content points towards a bog iron type. The presence of mineralized bacterial relics in the Hussainiyat goethite concretions and their framboidal, laminated and contorted texture support the bacterial role in their genesis. The stability of the land, low relief and gentle gradient together with long periods of exposure and pedogenesis gave rise to the development of a Fe-rich crust on top of sublithofacies B2. Iron disseminated in the kaolinite was mobilized upward (as Fe^{2+}) by capillary action in dry periods. The mobilized iron was deposited above the water table upon oxidation to Fe^{3+} producing various types of colloform ironstones by gradual in situ accretion of Fe-oxyhydroxide within the kaolinitic soil and finally forming autochthonous pisolitic-colloform ironstone (sublithofacies C1). The general character of the Hussainiyat pisolitic-colloform ironstone suggests a ferricrete deposit of groundwater origin developed in the manner described by Norton (1973), and Mann and Deutscher (1978).

The association of iron pisolites and oolites with botryoidal kaolinite-rich ironstone matrix of the same composition, color and character suggest in situ growth in soil. The colloform texture points towards deposition from a colloidal state. The common presence of radial cracks in the pisolites, not associated with hematite, supports this suggestion; these cracks resemble syneresis cracks usually developed from the dehydration and expulsion of water from colloidal material (Pettijohn, 1975). Concentric cracks, associated with minor amounts of hematite in the pisolites may be due to dehydration of goethite to hematite during diagenesis. The kaolinite-goethite interbands in the pisolites and oolites could be due to seasonal fluctuation of the Eh (Yakta, 1981). A low Eh enhances the dissolution of iron and retention of alumina (Petersen, 1971). However, Curtis and Spears (1968) attributed the interbanding in iron ooids to segregation during dehydration and crystallization.

The presence of two types of iron components, an Al-rich type and a Si-rich type, reflects different degrees of pedogenization and lateritization during the ferricrete development. The Al-rich type may have formed in the lower parts of the profile under lower Eh, whereas the Si-rich type was frequently above water table, subjected to subaerial exposure under more oxidizing conditions. Iron was precipitated from a colloidal state above the water table level producing the structureless massive sandy-silty ironstone (sublithofacies C3). Iron oxyhydroxides partly replaced the quartz grains and resulted in their corrosion along the outer boundaries. The intraclastic ironstone (sublithofacies C2) was developed by reworking of the previous ironstones (sublithofacies C1 and C3) and deposition with sand in the active parts, such as channel and wadi deposits, or with kaolinitic mud in quiet parts, such as lakes, ponds and overbanks. In the following stage, frequent sheet floods resulted in the deposition of the reddish-brown kaolinitic mudstone (sublithofacies B3) as floodplain deposits in the whole area, eventually covering the original ferricrete profile (sublithofacies C1) as well as the reworked ironstone deposits (sublithofacies C2) in the southern zone. The deposition of the Hussainiyat siliciclastics was then terminated by a phase of marine transgression, as thick tidal carbonate deposits were developed.

MINERAL RESOURCES OF SEDIMENTARY IRONSTONE IN IRAQ

The ironstone deposits in the Ga'ara Depression and SE Hussainiyat area have been extensively explored by Iraq Geological Survey since the eighties of the past century (Etabi and Dimitrov, 1982; Etabi *et al*., 1985; Maiqeel and Tamar-Agha, 1987; Abboud, 1990; Al-Qazzaz and Al-Ise, 1992; Mahdi and Husein, 1993; Husein and Jassim, 1993 and Jassim and Abdul Amir, 1998). The results of these investigations indicated about 80 m.t. of low-grade iron ores averaging <40% Fe_2O_3 with high impurities of kaolinite and quartz in the Hussainiyat Deposit and quartz in the Ga'ara (Chabid Al-Abid) Deposit (Table 4). Beneficiation tests to concentrate the iron minerals by economically feasible methods proved unsuccessful and the reserves are smaller than the requirements of the steel industry. These deposits have been used to supply the cement industry (salts-resistant cement) by Fe-rich raw material since 1992. The reserves of Chabid Al-Abid Deposit are nearly exhausted now, but the mine at the SE Hussainiyat Deposit is still active.

Table 4: Reserve estimation of the ironstone deposits in the Western Desert

Deposit	Reserve C2 (m.t.)	Reserve C1 (m.t.)	Reserve B (m.t.)	Fe_2O_3 (wt.%)	Al_2O_3 (wt.%)	SiO_2 (wt.%)	Reference
Hussainiyat	17.3	45.8		26.48	14.51	34.83	Etabi *et al*., 1985
Hussainiyat		0.47		39.32	18.70	28.78	Abboud, 1990
Hussainiyat			1.94	26.9 – 39.49	19.85 – 21.9	26.9 – 33.7	Al-Qazzaz and Al-Ise, 1992
Hussainiyat			12.6	25.5 – 27.38	14.2 – 19.6	28.5 – 35.56	Mahdi and Husein, 1993
Hussainiyat			0.04	30.0 – 31.1	15.33 – 18.1	31.95 – 37.7	Husein and Jassim, 1993
Ga'ara – Chabid Al-Abid (Floats)			0.113	30.2 – 51.5	0.3 – 2.8	36.7 – 54.9	Maiqeel and Tamar-Agha, 1987
Ga'ara – Chabid Al-Abid (outcrops)			0.493	22.4 – 46.9	0.3 – 0.5	45.0 – 76.0	Maiqeel and Tamar-Agha, 1987
Ga'ara-Chabid Al-Abid			0.18	39.5	0.59	54.12	Jassim and Abdul Amir, 1998.
Ga'ara- unspecified	2.6			35.23			Vasiliev *et al.*, 1964

CONCLUSIONS

- The main sedimentary ironstone deposits of Iraq are located in the Western Desert. Two main deposits are investigated and assessed; the Hussainiyat Deposit (Lower Jurassic), which is the largest in Iraq of its type, and the Ga'ara Deposits (Permocarboniferous). Both deposits are of continental origin, developed in fluvial systems and influenced by pedogenesis to various degrees. The source materials are highly weathered igneous, metamorphic and older sedimentary rocks of the Arabian Shield, transported to the depositional sites by rivers.
- The ironstone deposits usually form lenticular beds, associated with quartzose sandstone and kaolinitic mudstone. Various textural types of ironstone are identified; the most prominent of which are pisolitic-oolitic ironstone, fragmentary intraclastic ironstone, sandy ironstone and concretionary ironstone. The iron mineralogy is dominated by goethite and hematite and the non-iron minerals are mainly kaolinite and quartz. Iron concentration in these deposits is highly variable, but generally range from 20 to 50 wt. % Fe_2O_3 depending on the amount of iron minerals in the deposits.
- The Iraqi resources of sedimentary ironstone are limited to the deposits of the Western Desert which are estimated to contain about 80 m.t. raw iron ore with average grade

ranging between 25 and 40 wt. Fe_2O_3. Due to the high content of kaolinitic and silica impurities, low grade and limited reserves, these deposits are used in the cement industry only.

REFERENCES

Abboud, A., 1990. Report on the results of geological prospecting in Al-Hussainiyat shoulders for first locality. GEOSURV, int. rep. no. 1847.

Abboud, D. and Mansour, J., 1965. Report on geological investigation into area of the Wadi Al-Hussainiyat. GEOSURV, int. rep. no. 315.

Al-Bassam, K.S. and Jassim S.Z., 1983. Reconnaissance exploration for bauxite minerals in the Jurassic and Cretaceous rocks of the Western Desert, Iraq. GEOSURV, int. rep. no. 1416.

Al-Bassam, K.S. and Tamar-Agha, M.Y., 1998. Genesis of the Hussainiyat iron deposit, Western Desert, Iraq. Miner. Deposita, Vol.33, p.266 – 283.

Al-Hashimi, W. and Skoček, V., 1981. Composition and origin of sedimentary iron ores, Lower Liassic, Western Desert, Iraq. GEOSURV, int. rep. no. 1235.

Al-Naqib, S.Q., Ma'ala, K.A. and Saeed, L.Kh., 1984. Detailed geological mapping of Wadi Rejlat Al-Dabe. GEOSURV, int. rep. no. 1561.

Al-Naqib, S.Q., Saeed, L.Kh, Taha, M., Al-Sharbati, F., Nouri, S., Salman, M., Isko, I. and Izzeldin, L., 1986. Detail geological survey of Rutba area. GEOSURV, int. rep. no. 1560.

Al-Qazzaz, H. and Al-Ise, J.H., 1992. Detailed geological prospecting for iron in eastern Wadi Al-Hussainyat, Category B, Quarry no.3 and 4. GEOSURV, int. rep. no. 2054.

Al-Youzbaky, Q.T., 1989. The Mineralogy and geochemistry of the iron associated with the kaolinite of the Ga'ara Formation. University of Mosul, College of Science. (In Arabic).

Alsayegh, A.H., Tamar-Agha, M.Y. and Al-Youzbaky, K.T., 1994. The Geochemistry of iron in the mudrocks of the Ga`ara Formation in the Iraqi Western Desert. Iraqi Geol. J., Vol.27, No.2 , p. 1 – 19.

Aubert, H. and Pinta, M., 1977. Trace Elements in Soils. Developments in Soil Science, Vol.7. Elsevier, Amsterdam. 1754pp.

Boulange, B., Carvalho, A. and Melfi, A., 1990. Geochemical characteristic of African and Brazilian bauxites deposits: SiO_2-Al_2O_3-Fe_2O_3 system and Ti, Cr, V, and Fe_2O_3 relations. Chem. Geol. Spec. Issue, Vol.84, p. 30 – 32.

Buday, T., 1980. The Regional Geology of Iraq. Vol.1, Stratigraphy and Paleogeography. In: I.I., Kassab, and S.Z., Jassim, (Eds.). University of Mosul, Dar Al-Kutub. GEOSURV, Baghdad, 445pp.

Buday, T. and Hak, J., 1980. Report on the geological survey of the western part of the Western Desert, Iraq. GEOSURV, int. rep. no. 1000.

Buday, T. and Jassim, S.Z., 1987. The Geology of Iraq, Vol.2, Tectonism, Volcanism and Magmatism. In: I.I. Kassab and M.J. Abbas (Eds.). University of Mosul, Dar Al-Kutub. GEOSURV, Baghdad, Iraq, 352pp.

Canavan, R.W., Van Cappellen, P., Zwolsman, J.J.G., Van den Berg, G.A. and Slomp, C.P., 2007. Geochemistry of trace elements in fresh water sediment: field results and diagenetic modeling. Sci. Total Environ, Vol.381 p. 263 – 279.

Chaikin, S.I., 1970. On iron ore potentialities in Iraq and recommendations on the trend of further geological iron ore exploration. GEOSURV, int. rep. no. 548.

Ctyroky, P., 1971. Preliminary paleontological report on samples from the Ga'ara area. GEOSURV, int. rep. no. 513.

Curtis C.D. and Spears, D.A., 1968. The formation of sedimentary iron minerals. Econ. Geol., Vol.63, p. 257 – 270.

Etabi, W. and Dimitrov, D., 1982. Report on stage I geological investigation of the Hussainiyat iron ore deposit (Part 2). GEOSURV, int. rep. no. 1245.

Etabi, W., Abboud, A. and Houbi, W., 1985. Report on mineral investigation of the Hussainiyat iron ore deposit. Stage II, Part1: Geology and reserve estimation. GEOSURV, int. rep. no. 1441.

Fouad, S.F., 2012. Tectonic Map of Iraq- Scale 1: 1000 000 (3rd edition). GEOSURV, Baghdad, Iraq.

Hassan, K.M., 1985. Jurassic mollusca from Western Desert, Iraq. M.Sc. Thesis, University of Hull, UK.

Husein, J.A. and Jassim, A., 1993. Investigation of iron in the Hussainiyat border (reserve estimation). GEOSURV, int. rep. no. 2080.

Ibanga, I.J., Boul,S.W.,Weed, S.B. and Bown, L.H., 1983. Iron oxides in petroferric materials. Soil Sci. Soc. Am. J., Vol.47, p. 1240 – 1246.

Jassim, A. and Abdul Al-Amir, W., 1998. Mineral investigation and reserve estimation for the Chabid-Al-Abid iron according to the category B, Ga'ara depression, western Desert. GEOSURV, int. rep. no. 2438.

Jassim, S.Z., Khalil, A., Al-Bassam, K.S., Shehata, I., Abdul-Wahid, K., Said, Y. and Safo, J., 1981. Hussainiyat iron exploration project Geological, geochemical and geophysical exploration. GEOSURV, int. rep. no. 1109.

Jassim, S.Z., Karim, S., Al-Mubarek, M., Basi, M. and Munir, J., 1984. Final report on the geological survey of Iraq, 3: Stratigraphy. GEOSURV, int. rep. no. 1447.

Jassim, S.Z., Hagopian, D. and Al-Hashimi, H., 1987. Geological Map of Iraq, scale 1: 1000 000 (1st edittion). GEOSURV, Baghdad, Iraq.

Lange, H., 1975. Petrographic and mineralogical examination of samples coming from the Al-Hussainiyat and Al-Ga'ara ore bodies in Iraq. GEOSURV, int. rep. no. 730.

Mahdi, M.A. and Husein, J.A., 1993. Evaluation of iron ores, kaolinite and dolomite in Al-Hussainiyat locality (First Stage). GEOSURV, int. rep. no. 2205.

Maiqeel, W.A. and Tamar-Agha, M.Y., 1987. Report on the exploration on ironstone deposits at the Ga'ara depression. GEOSURV, int. rep. no. 1552A.

Mann, A.W. and Deutscher, R.L., 1978. Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia. Econ. Geol. Vol.73, p. 1724 – 1737.

Mason, B., 1966. Principles of Geochemistry (3rd edition). J. Wiley, New York. 195pp.

Misra, K.C., 1999. Understanding Mineral Deposits. Kluwer Academic Publishers, New York, 845pp.

Norton, S.A., 1973. Laterite and bauxite formation. Econ. Geol. Vol.68, p. 353 – 361.

Petranek, J. and Jassim, S.Z., 1980. Iron ore deposition within Arabian Peninsula in time and space. J. Geol. Soc. Iraq, Vol.13, p. 179 – 186.

Pettijohn, E.J., 1975. Sedimentary Rocks (3rd ed.). Harper and Row, New York. 1613pp.

Petersen, U., 1971. Laterite and bauxite formation. Econ. Geol., Vol.66, p. 1070 – 1071.

Philip, G., Saadallah, A. and Ajina, T., 1968. Mechanical analysis and mineral composition of the Middle Triassic Ga'ara sandstone, Iraq. Sed. Geol. Vol.2, p. 51 – 76.

Radosevic, B. and Lesevic, Z., 1981. The results of paleogeographic investigations in wider Rutba area, Western Desert, Iraq (abstract). In: Abstract Book of the 6th Iraqi Geological Congress. Al-Zahra'a Press, Baghdad, Iraq, 37pp.

Rankama, K. and Sahama, T.G., 1950. Geochemistry. University of Chicago Press, Chicago, 912pp.

Rogers, J.I. and Adams, J.A.S., 1969. Thorium-Uranium. In: K.H. Wedepohl (Editor.), Handbook of Geochemistry V. II, Springer Verlag, Berlin, Heidelberg, New York.

Ronov, A.B. and Yaroshevsky, A.A., 1969. Chemical composition of the Earth's crust. In: Hart, P.J. (ed.) The Earth's crust and upper mantle. (Monograph 13D) American Geophysical Union, Washington DC, p. 37 – 57.

Ronov, A.B. and Yaroshevsky, A.A., 1972. Earth's crust geochemistry. In: R.W. Fairbridge (Editor.) The Encyclopedia of Geochemistry and Environmental Sciences. Van Nostrand Reinhold, p. 243 – 254.

Rudnick, R.L. and Gao, S., 2003. Composition of the continental crust. Treatise on Geochemistry. Elsevier Ltd. Vol.3, p. 1 – 64.

Rigaud, S., Radakovitch, O., Couture, R.M., Deflande, B., Cossa, D., Garnier, C. and Garnier, J.M., 2013. Mobility and fluxes of trace elements and nutrients at the sedimentwater of lagoon under contrasting water column oxygenation conditions. Appl. Geochem. Vol.31, p. 35 – 51.

Sadiq, A.J., 1985. Surface- subsurface mineralogical geochemical study of clays and iron ores of Paleozoic rocks in Western Desert, Iraq. Unpublished M.Sc. Thesis, University of Baghdad, 182pp.

Salman, H.H., 1977. Sedimentology of the upper part of Ga'ara Formation, Western Iraq. Unpublished M.Sc. Thesis, University of Baghdad, 118pp.

Skoček, V., Al-Qaraghuli, N. and Sa'adallah, A., 1971. Composition and sedimentary structures of iron ores from Wadi Hussainiyat area. Econ. Geol., Vol.66, p. 995 – 1004.

Stanton, R.L., 1964. Mineral interfaces in stratiform ores. Inst. Mining. Metall. Trans. Vol.74, p. 45 – 79.

Tamar-Agha, M.Y., 1986. The detailed geological mapping of the southern rim of Ga'ara depression, part 1. GEOSURV, int. rep. no. 1779.

Tamar-Agha, M.Y., 1993. Prospecting and exploration in the Western Desert (1986 – 1990). Part 1: General Geology. GEOSURV, int. rep. no. 1899.

Tamar-Agha, M.Y. and Abdullah, H.H., 2013. Morphodynamics, landform development and origin of the Ga'ara Depression, Western Desert of Iraq. Arab. J. Geosci., DOI 10.1007/s12517-013-1000-8 (online paper).

Tamar-Agha, M.Y., Numan, N.M.S. and Al-Bassam, K.S., 1997. The Ga'ara anticline in Western Iraq, a structural fiasco. Rafidain J. Sci. Vol.8, No.2, p. 56 – 70.

Technoexport, 1965. Description of trial manufacture samples collected from Al-Ga'ara and Hussainiyat iron ore deposits. GEOSURV, int. rep. no. 476.

Tobia, F.H., 1983. Geochemistry and Mineralogy of the Iron Ore Deposits of Ga'ara Formation in Iraqi Western Desert. Unpublished M.Sc. Thesis, University of Baghdad, 156pp.

Tobia, F.H., Kettanah, Y.A. and Mustafa, M.M., 2014. Petrography and geochemistry of Ga'ara sedimentary ironstones, Western Desert of Iraq, Jour. African Earth Sciences Vol.97, p. 261 – 272.
Vasiliev, M.M., Polnikov, G.A. and Vexlar, V.I., 1964. Report on geological investigations into iron ore of the Al-Ga'ara. GEOSURV, int. rep. no. 314.
Watanaba, K., 1987. Geochemical behavior of iron and manganes ions in the Ningyo-Toge uranium deposit district, Southwest Japan. Chemical Geology, Vol .60, p. 299 – 307.
Yakta, S.A., 1972. Investigation in the Al-Ga'ara area. GEOSURV, int. rep. no. 574.
Yakta, S.A., 1981. Ironstone Sedimentation in the Western Desert, Iraq. M.Sc. Thesis, University of Wales, U.K., 256pp.
Yakta, S.A., 1984. Petrography, mineralogy and genesis of Hussainiyat ironstone, Western Desert, Iraq. GEOSURV, int. rep. no. 1393.

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