

KARST BAUXITE DEPOSITS OF NORTH HUSSAINIYAT AREA, WESTERN DESERT, IRAQ: AN OVERVIEW

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ABSTRACT

The North Hussainiyat karst bauxite deposits in the Western Desert of Iraq are the only known bauxite resources in Iraq. They were discovered by Iraq Geological Survey in 1990 as few meters to 35 m thick lenses in fossil karsts of various sizes in the Ubaid Formation (early Lower Jurassic), associated with bauxitic kaolinite, kaolinite, flint-clay and quartz sandstone. Some strongly bauxitic profiles reach up to 100 m in thickness. They are pisolitic or massive in texture and composed of boehmite, gibbsite, kaolinite and accessory amounts of anatase. The bauxite lenses are sandwiched between the underlying bottom sandstone and kaolinitic mud rocks and the overlying top clay, which is dominated by kaolinite, quartz and goethite. Geochemical data suggest that the immobile elements such as Al_2O_3 , TiO_2 , Cr, Zr, and Ni were enriched, while SiO_2 , Fe_2O_3 , CaO, MgO, Zn, Co, Ba, Mn, Cu and Sr were depleted during the bauxitization process. The results of various studies strongly suggest that these karst bauxite deposits were derived from the kaolinitic clay deposits of the Hussainiyat Formation (late Lower Jurassic). The age of these bauxite deposits is controversial; some authors suggest they are of Early Cretaceous (Aptian – Albian) age whereas others believe they are of Lower – Middle Jurassic age and some authors suggested Paleocene – Eocene age based on their pollens and spores content. High grade bauxites are scarce and most of the deposits are kaolinitic bauxite or bauxitic clays. The reserves were estimated by about 1.28 m.t., distributed in various karst deposits, and have been used in alum production and refractories, with limited laboratory experiments in alumina extraction.

رواسب البوكسيت الخسفي في منطقة شمال الحسينيات، الصحراء الغربية،
العراق: مراجعه عامة

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المستخلص

تعتبر رواسب البوكسيت الخسفية في منطقة شمال الحسينيات من الصحراء العراقية الغربية المصدر المعدني الوحيد المعروف للبوكسيت في العراق وقد اكتشفت في عام 1990 من قبل هيئة المسح الجيولوجي العراقية. يوجد البوكسيت بشكل عدسات يصل سمكها الى حوالي 35 متر في خسفات مندثرة في تكوين العبيد (الجوراسي الاسفل) بصحبة أطياف كاؤولينية وكاؤولينية بوكسايتية وطين فلنتي وحجر رملي مروي وقد يصل سمك المقطع البوكسايتي الى 100 متر أحيانا. يسود النسيج الحمصي والكتلي في هذه الرواسب وتتكون من البوهمايت والجيبسايت والكاؤولينايت وكميات قليلة من الاناتيز. تنحصر العدسات البوكسايتية بين حجر رملي مروي ووحل كاؤوليني في الأسفل وبين أطياف كاؤولينية حديدية وغرينية في الأعلى. تشير المعطيات الجيوكيميائية الى حصول إغناء بالالومينا والتيتانيا والكروم والزركون والنيكل وخب

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للسيليكا والحديد والكالسيوم والمغنيسيوم والزنك والكوبلت والباريوم والمنغنيز والنحاس والسترونتيوم خلال عملية البكستة. تشير معظم الدراسات الى ان مصدر هذه الرواسب البوكسائيتية هي الأطيان الكاؤولينيتية لتكوين الحسينيات (الجوراسي الاسفل) وهناك عدة مقترحات متباينة بشأن عمر هذه الرواسب حيث يعتقد بعض الباحثون انها تكونت خلال العصر الطباشيري المبكر (ابتيان-البیان) وآخرون يرون انها تكونت خلال الجوراسي الأسفل الى الجوراسي المتوسط وهناك من يقترح انها من عمر الإيوسين. الرواسب البوكسائيتية الغنية قليلة في هذه الرواسب ومعظم الخامات هي بوكسائيت كاؤولينيتي او كاؤولين بوكسائيتي وقد قدرت الاحتياطيات في عدة خسفات بحوالي 1.25 مليون طن استعمل جزء منها في صناعة الشب والحراريات مع تجارب مختبرية محدودة لاستخلاص الألومينا.

INTRODUCTION

Bauxite is known as the primary raw material of aluminum, and is commonly formed as a result of intense chemical weathering in hot and humid zones, representing a typical exogenous type of mineral resource (Bárdossy, 1982; Beiranvand *et al.*, 2007; Bogatyrev *et al.*, 2009; Horbe and Anand, 2011; Mondillo *et al.*, 2011; Gamaletsos, 2014; Ahmadnejad *et al.*, 2017). Bauxite deposits can be classified into two main types based on the bedrock lithology: bauxite deposits overlying aluminosilicate rocks are defined as lateritic bauxites, and bauxite deposits lying on carbonate rocks are identified as karstic bauxites (Bárdossy, 1982). The presence of bauxite in the Iraqi Western Desert was reported for the first time by GEOSURV geologists (Mustafa, 1991) following extensive exploration work by GEOSURV geologists (Al-Bassam and Jassim, 1983; Mustafa *et al.*, 1990).

The discovered bauxites are hosted in fossil karsts developed in the carbonate rocks of the Ubaid Formation (early Lower Jurassic), widespread in the Hussainiyat area northeast of Rutba city in the Iraqi Western Desert. Geographically, the area covers 700 Km² within 40° 59' to 41° 27' East longitude and from 33° 22' to 33° 37' North latitude (Fig.1). The bauxite in the North Hussainiyat area was developed in fossil karsts, tens of meters deep and hundreds of meters wide, concentrated in areas where maximum intersection of fractures and faults exist. Most bauxite bodies are lenticular in shape with thickness ranges from few meters to 35 m and in some place reach up to 100 m. The age of the bauxites is controversial. It was suggested by some GEOSURV geologists as Early Cretaceous (Aptian – Albian) (Fig.2) based on field observations, regional stratigraphic correlations and paleoclimatic conditions (Al-Bassam, 1996; Mustafa and Jibrial, 1996; Mustafa *et al.*, 1997). A Lower – Middle Jurassic age was proposed by Al-Atia and Sa'adallah (1996) on the basis of climatic conditions and correlation with the clastic unit of the Hussainiyat Formation. An age of Paleocene – Eocene was suggested by Al-Ani (1996) and Al-Rawi *et al.* (1996), on the basis of pollen and spores analysis of the underlying and overlying rock units (Fig.3).

GEOLOGICAL SETTING

Tectonically the studied area is part of the Inner Platform of the Arabian Plate (Fouad, 2012) and the Rutba Subzone of the Rutba – Jezira Zone of the Stable Shelf according to Budy and Jassim (1987) terminology. This area is dominated by the Rutba uplift (Horan High according to Al-Bassam *et al.*, 2005), which is a swell developed during the Mesozoic-Tertiary movements and reflected in the sedimentary cover since the Triassic but not in the basement structure (Jassim *et al.*, 1984). The uplift was a result of a long-lasting evolution and was mostly covered by a shallow sea, but some parts in the NE were frequently land. It acted as a basin divide since the Cretaceous, where different marine facies were developed on either side of the swell (Al-Bassam *et al.*, 1990). The present day expression of the uplift is found in the Paleozoic window in the Ga'ara depression, high relief of geomorphological features, ground water divide and high density of lineament intersections (Al-Bassam *et al.*, 2005).

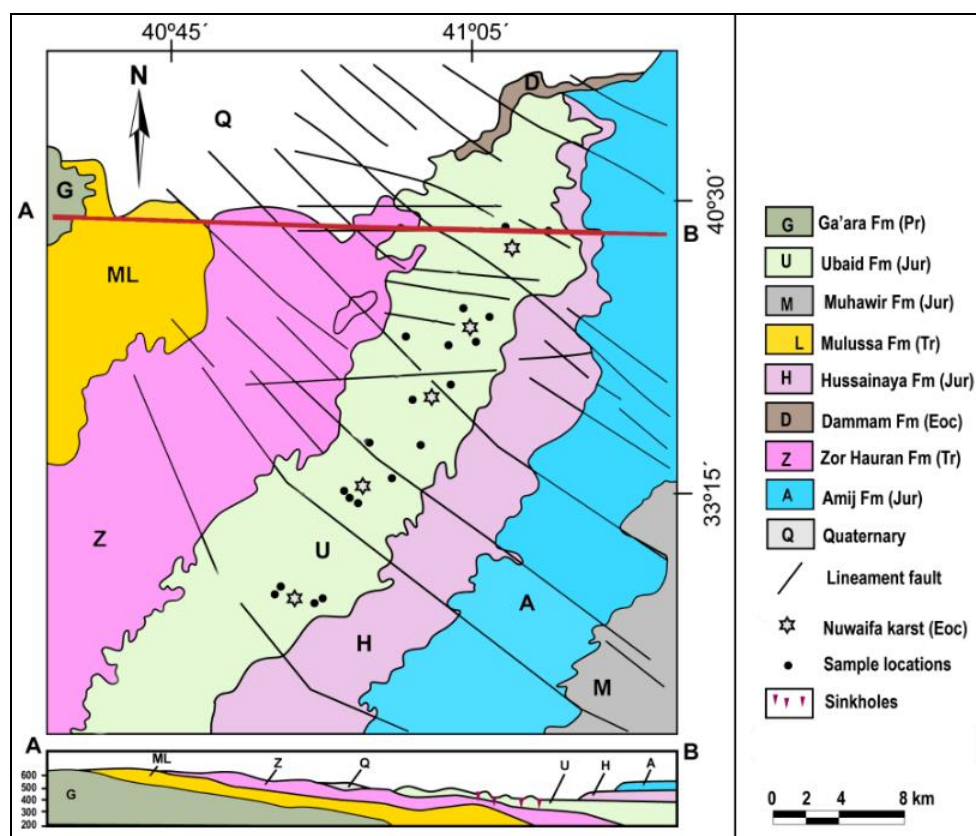


Fig.1: Simplified geological map of the area (modified after Mustafa *et al.*, 1994)

Age	Iraqi Western Desert Sequence	W. Desert Karst Sequence
Early Miocene	Euphrates/ Ghar	Ghar
Oligocene	Shaikh Alas/ Shaurau	
Eocene	Dammam/ Ratga	Ratga
Paleocene	Umm Er Radhuma/ Akashat	
Cretaceous	Late	
	Early	Quartzite Bauxitization Bauxite
Jurassic	Malm	Najma
	Dogger	Muhawir Amij
	Liassic	Hussainiyat Ubaid
	Late Triassic	Zor Hauran Mulussa

Fig.2: Stratigraphic position of the karst bauxite according to Al-Bassam (1996)

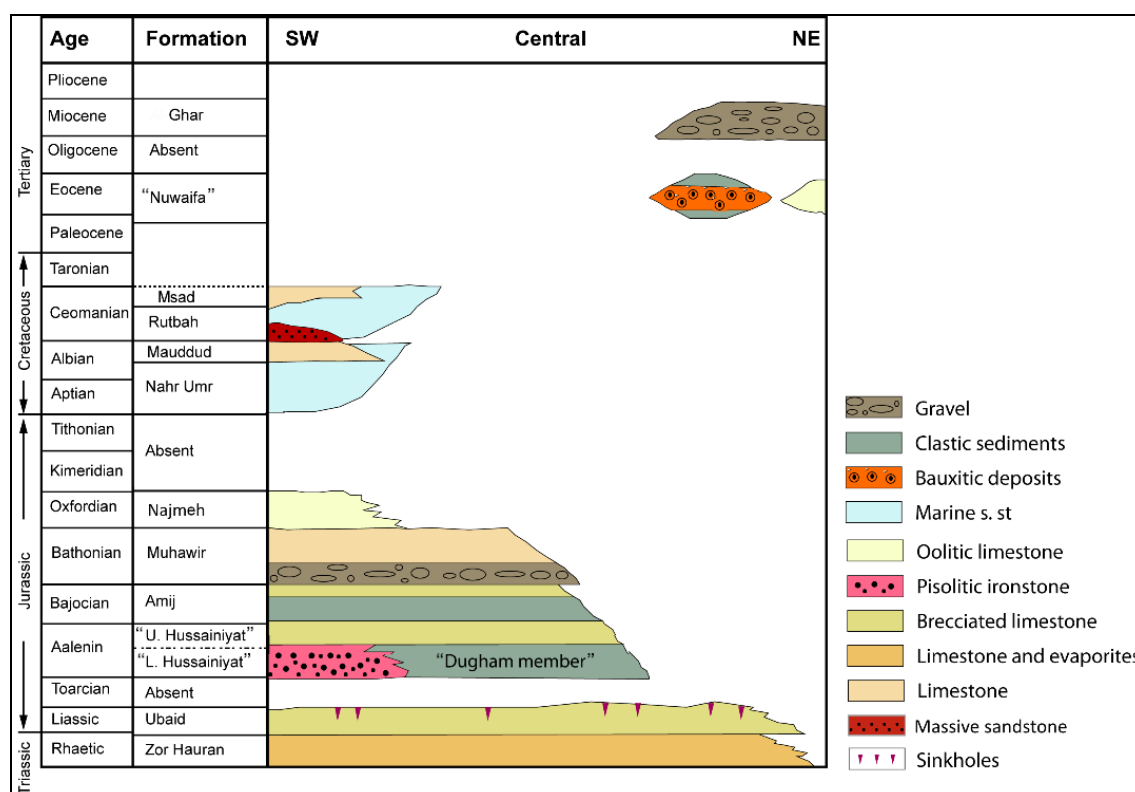


Fig.3: Stratigraphic position of the karst bauxites according to Al-Ani (1996 and 2017)
(Terms between inverted commas are informal names)

During Late Jurassic – Early Cretaceous, the area was affected by the Early Cimmerian Orogeny (collision of Arabian-Turkish-Iranian plate (Alavi, 1994) which led to a relative uplift of the Hauran Basin marking a second major break of sedimentation in the area (Qassir *et al.*, 1992). This was accompanied by deep erosion leaving parts of the surface of carbonate rocks of the Ubaid Formation exposed again to deep weathering furnished by contemporaneous change in climatic conditions towards wet and warm tropical climate. The top of the Ubaid Formation is marked by an erosional unconformity, partly overlain by the Hussainiyat Formation which consists of fluvial clastics at base and shallow marine carbonates at top.

The stratigraphy of the area was studied by GEOSURV geologists (e.g. Karim and Ctyroky, 1981; Al-Mubarak and Amin, 1983; Jassim *et al.*, 1984; Al-Mubarek, 1996; Al-Azzawi and Dawood, 1996; Mustafa *et al.*, 1996; Jassim and Buday, 2006 and Sissakian and Mohammed, 2007). The geology of the central part of the Western Desert was described in detail by Al-Mubarak (1996) and the Early Jurassic sequences, where the bauxites are hosted, were described as follow:

– **Ubaid Formation (Liassic):** It represents the first Jurassic sedimentary cycle in the Iraqi Western Desert, unconformably overlying the Zor Hauran Formation (Upper Triassic). It varies in thickness from a few meters near Rutba town in the west to 95 m near Wadi Hauran in the east. The formation was deposited in a shallow marine environment and is comprised, from bottom to top, of 28 m dolostone or dolomitic limestone with chert nodules; 40 m dolomitized shelly limestone with marl intercalations and 20 m of gypsiferous marl and

recrystallized shelly limestone. The contact with the overlying Hussainiyat Formation is undulated in subsurface and karstified in outcrops.

– **Hussainiyat Formation (Liassic):** It represents the second Jurassic sedimentary cycle in the Western Desert and consists of a lower clastic member of continental origin (fluvial and pedogenic) and an upper carbonate member of shallow marine origin. Both members pinch out towards the west. The lower member is up to 54 m thick near Wadi Hauran and consists of alternations of sandstone and kaolinitic claystone with occasional pisolitic and concretionary ironstone lenses. The upper part of the lower member is comprised of alternations of shelly and algal limestone and sandstone, marking early signs of marine transgression. The upper member of the Hussainiyat Formation is 56 m thick in the NE part of the area, but reduced to a few meters thick in the SW part. It is composed of chert-bearing dolostone and dolomitic fossiliferous limestone. The Hussainiyat Formation is unconformably overlain by the Amij Formation which represents the third Jurassic sedimentary cycle in the area.

THE BAUXITE-BEARING SEQUENCE

The karst-fill sedimentary sequence was described by Mustafa *et al.* (1994 and 1996) and Al-Ani, (1996). An informal name of “Nuwaifa Formation” with two members was proposed by Mustafa *et al.* (1994) and used by Al-Ani (1996). According to previous work, the bauxite-bearing karst-fill deposits of the Hussainiyat area exhibit similar pattern of sedimentary succession in most of the investigated karsts (Fig.4). The filling sediments are usually concave upwards, having the general shape of the karst. Lithologically, the stratum containing the ore body includes four individual lithofacies, namely; **(a)** kaolinitic bauxite; **(b)** bauxitic kaolinite; **(c)** iron rich bauxite and **(d)** flint clay (Figs.4 and 5). These bauxite lithofacies appear as pockets and lenses scattered throughout the karst depressions.

- a) **Kaolinitic bauxite.** It has a thickness of approximately 2 – 6 m and represents the high-grade ore. The lithofacies is characterized by a light colour and the presence of textural characteristics such as spherical components, often present as pisoids and ooids with various shapes and sizes (Fig.6). In this lithofacies the pisolite grain size (3 – 20 mm) is larger than in other bauxite layers, and shows an increase in size and abundance of the pisolitic grains upwards (Fig.6a). The pisolitic horizon is physically harder and denser than the others, and varies from light to grey colour. Massive structure and higher hardness than other lithofacies are the most important macroscopic characteristics of the pisolitic ores. Minerals identified in this lithofacies include boehmite and gibbsite, with lesser kaolinite and anatase. This lithofacies is formed by intensive leaching within karst depression removing most of the iron, silica, and other trace elements from the alluvial sediments to form low-Fe bauxite.
- b) **Bauxitic kaolinite lithofacies.** It is found at the top of profiles with variable thickness in the range of 0.5 – 2.5 m, overlying kaolinitic bauxite and iron-rich bauxite (Figs.4 and 5). Mineralogically, this lithofacies consists mainly of kaolinite and boehmite (<10%), with lesser hematite and anatase, which represents the transition towards the clay and bauxite ores. The lithofacies is characterized by a decrease in abundance pisolitic grains with low oolite/ matrix ratio, non-plastic, soft and white to grey in colour. This facies formed by chemical weathering and leaching related to stronger drainage condition within the buried alluvial sediments, which removed iron from the kaolinitic clay to transform it into low-Fe bauxitic facies. The texture of this facies is very poorly sorted oolitic and pisolitic float in a

structureless matrix. In this case, it may be inferred that bauxite is formed in place (Maynard, 1983).

- c) Iron rich bauxite. It is represented by pisolitic layers with a thickness of approximately 2 – 4 m. The mineralogy is dominated by the presence of boehmite and Al-hematite, which are the main phases, with minor kaolinite, goethite and anatase. The cores of the ooids generally consist of older, detrital bauxite grains (bauxite pebbles), or of hematite-goethite fragments. Boehmite and hematite are more abundant in the ooids, whereas kaolinite is found at higher levels in the groundmass. However, in the structure of most ooids, boehmite and kaolinite are concentrically zoned, following a well-known diagenetic pattern suggested to reflect different climate conditions during bauxite formation (Bárdossy, 1982).
- d) Flint clay: It is composed predominantly of well-crystallized kaolinite, mostly white in color, very fine grained, and hard with conchoidal fractures. The central part of the lithofacies is composed of poorly crystallized kaolinite, whereas the rims are composed of well crystallized kaolinite. The general appearance and degree of kaolinite crystallinity indicate that the original fragments (represented by the central part) have been gradually altered to produce authigenic, well-crystallized kaolinite at the rims.

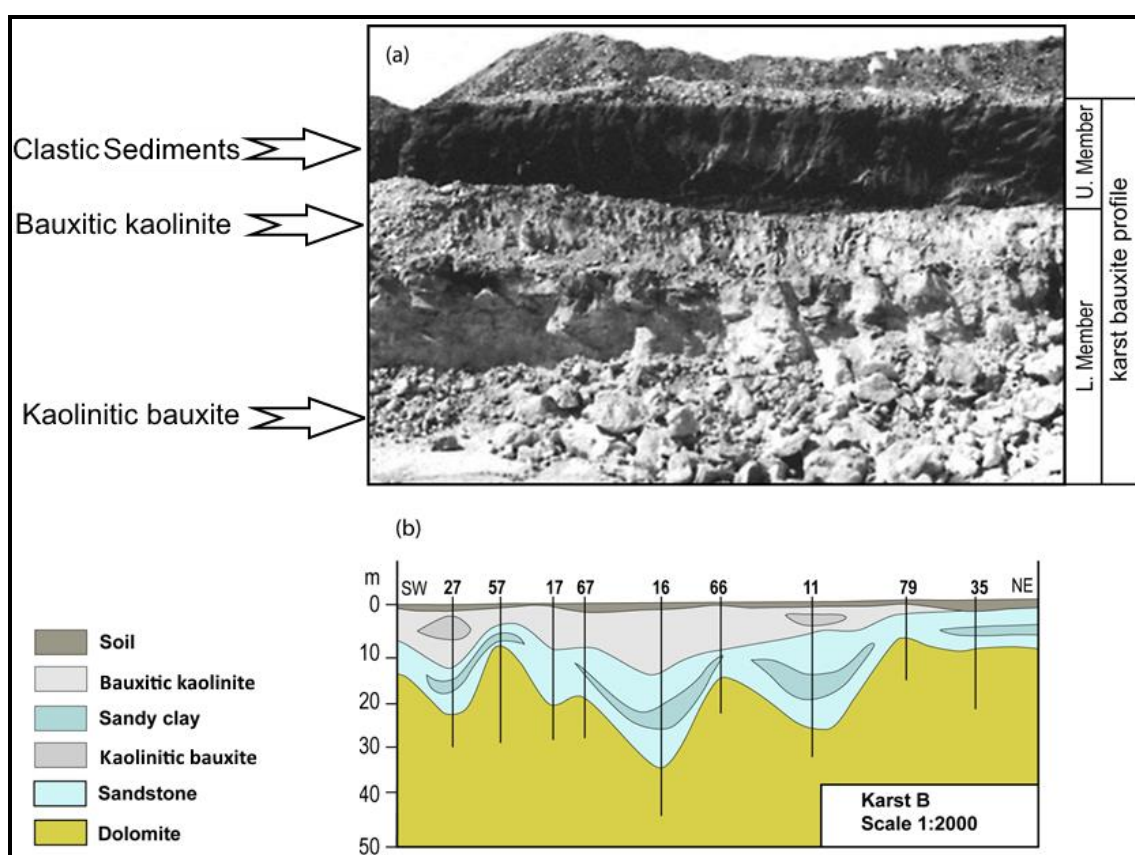


Fig.4: **a)** An exposed quarry face showing bauxite and flint clay deposits (Lower Member) and clastic sediments (Upper Member); **b)** Cross-sections of karst bauxite deposits (Modified after Al-Ani, 1996)

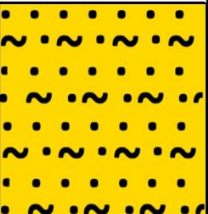

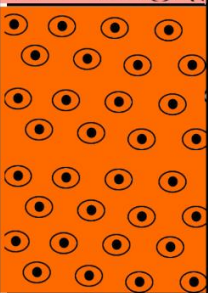
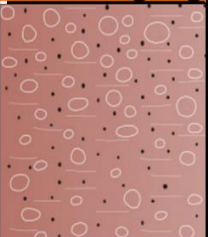


Deposit types	Member	Stratigraphic columns	Thickness (m)	Lithologic features
Karst bauxite profile	Upper Member		3–20	Clastic Sediments composed mainly of sandstone, claystone and mudstone
	Lower Member		0.5–2.5	Bauxitic- kaolinite with low oolitic/matrix ratios and moderate bauxitization.
			2–6	Kaolinitic bauxite and bauxite characterized by pisoidal- ooidal texture; with high oolitic/matrix ratios and strong bauxitization. The bauxite minerals are colloformic in texture including pisoids, ooids, peloids and brecciated bauxite textures (Fig. 5).
			2–4	Iron-rich bauxite consists of bauxite and disordered kaolinite with segregate of iron oolites and pisolites in a matrix. Characterized by high oolitic/matrix ratios and developed under subaerial oxidizing conditions
			0–10	Flint clay as well-crystallized kaolinite, mostly white in colour and hard with conchoidal fractures and contain iron nodules
Ubaid Formation	karstified limestone		>70	Dolomitic limestone with moderately to strongly karstified surface, which hosted bauxite deposits.

Fig.5: Columnar section of the bauxite-bearing horizons
(Modified after Al-Ani, 1996)

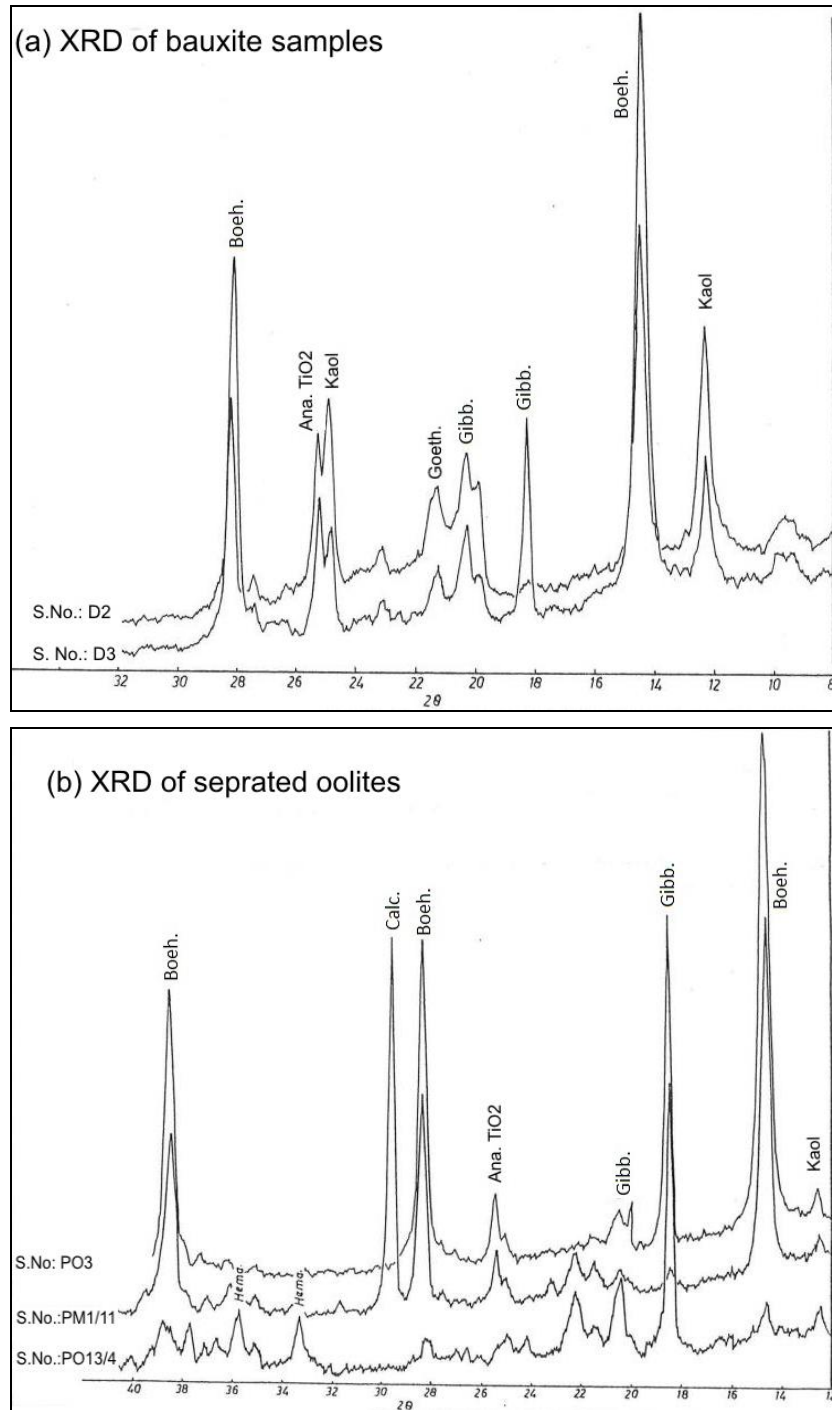


Fig.6: **a)** X-ray diffractograms of the bulk bauxite showing the main minerals identified;
b) X-ray diffractograms of the separated bauxite pisolites (Al-Ani, 1996)

BAUXITE TEXTURE AND MINERALOGY

Detailed mineralogical and textural studies of bauxite deposits based on optical microscopy and X-ray diffraction (XRD) data revealed that the mineralogical composition is dominated by boehmite, identified by the XRD peaks at 6.11, 3.16 Å and minor amount of gibbsite, with identified peaks at 4.85, 4.37 Å (Fig.6). Boehmite was found in all of the studied bauxite samples, while gibbsite is found only in 35%. Anatase occurs in both the

matrix and the oolites. Highly kaolinitized bauxite is characterized by a white matrix, composed only of kaolinite (Fig.6a). Small amounts of kaolinite are also present in the bauxite body filling joints or cementing oolites (Fig.6b).

The petrology of the karst bauxites in North Hussainiyat is studied by various authors (e.g. Mustafa *et al.*, 1996; Al-Ani, 1996; Ali, 1997; Al-Bassam, 2005; Al-Ani, 2017). Two varieties of bauxite are found in the Hussainiyat karst area in the Western Desert of Iraq, low-iron bauxite, known as white ore, and a high-iron bauxite, known locally as red ore. Both bauxites share the same texture, which consists of sub-spheroidal structures (ooids) dispersed in a clayey fine grained matrix (Fig.7). The main mineralogical composition and structure of the ooids consist, in the majority of the cases, of an Al-hematite core and alternating concretions of Al-hematite and boehmite. The low-iron bauxite (white bauxite) is pisolitic and poorly to well cemented (Fig.7a). The pisolites occur as individual or composite pisolites and consist of concentric layers of uniformly colored, hard bauxitic minerals around a core that is commonly soft and clayey (Fig.7b).

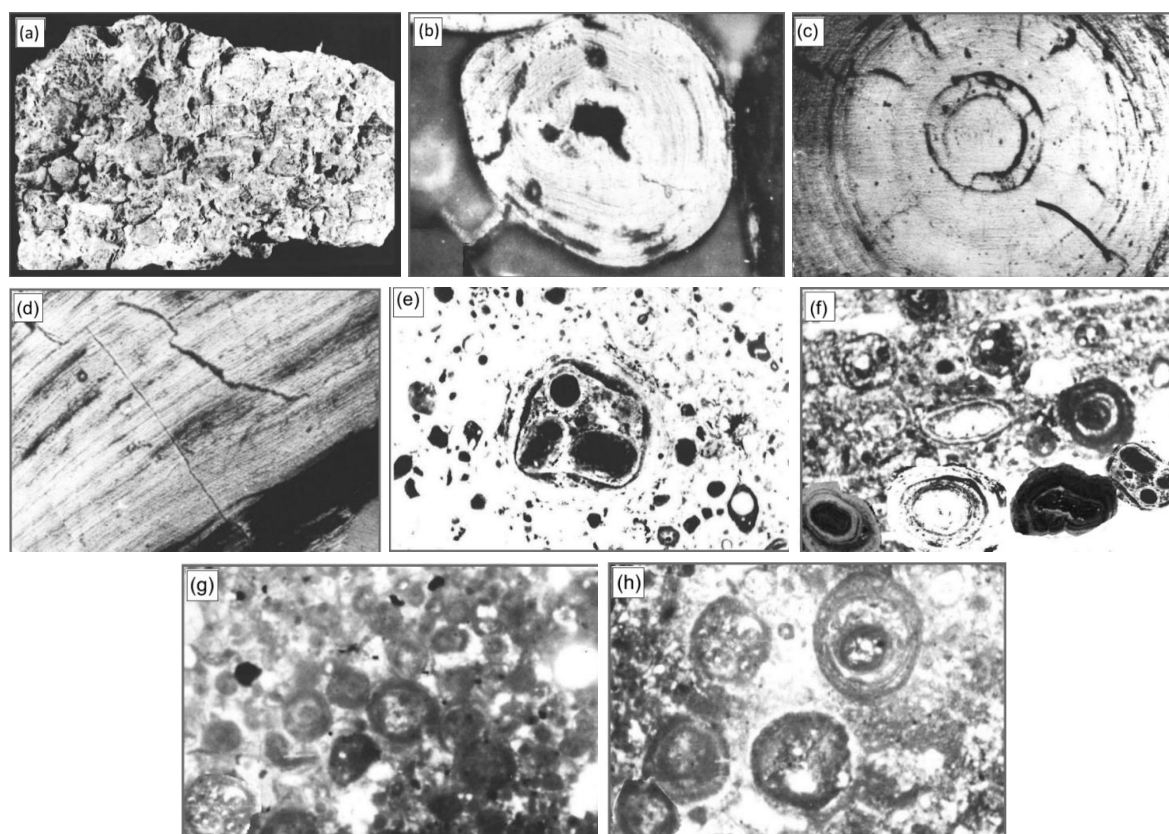


Fig.7: Petrography of the bauxite ore (Al-Ani, 1996); **a)** Pisolithic bauxite; **b)** Pisolithic bauxite embedded in a matrix made of kaolinite and iron oxides, using LEICA IM 1000 microscope (PPL); **c and d)** Coarse pisolite shows fractures filled by micrite and kaolinite; **e and f)** Development of composite pisolites embedded in a matrix made of kaolinite and iron oxides; **g and h)** Pisolithic iron-rich bauxite embedding red matrix, mainly hematite and kaolinite composition

The main mineralogical composition and structure of the ooids consist, in the majority of the cases, of a boehmite core and alternating concretions of kaolinite and boehmite (Fig.7b). Mineral components of the matrix in the bauxite ores are mainly cryptocrystalline kaolinite.

The pisolites are commonly 6 or 7 mm in diameter and of about the same hardness as the matrix. The number of shells within oolites and pisolites is between 4 and 7 and the diameter range from 3 to 20 mm (Fig.7c). Some oolitic and pisolitic textures observed in bauxites show the presence of fractures within the spherical grains that are filled with micrite and kaolinite. These fractures are often limited to pisolites (irregular and radial shapes) or cross the border of pisolites and extend into the matrix of the ores (Fig.7d). Composite ooids can also be noticed in the studied bauxite. They consist of several small ooids enveloped by concentric lamellae (Fig.7e and f), which may be the product of syn-depositional deformation and a discontinuity during the growing process of the ooids. In the pisolitic iron-rich bauxite samples, pisoids tend to be darker-colored and richer in iron than the embedding red matrix of mainly hematite and kaolinite composition (Fig.7g and h). The cores of the ooids generally consist of older, detrital bauxite grains or hematite, surrounded by a thin rim of Al-hematite. The pisolitic structure is made by the alternation of boehmite and Al-hematite layers, reflecting dry and wet climate periods respectively (Fig.7f – h).

GEOCHEMISTRY

The geochemistry of the North Hussainiyat karst bauxites was studied by several authors (e.g. Al-Ani, 1996; Ali, 1997; Al-Bassam, 2005; Al-Ani, 2017). The analytical results of major and trace elements of 92 representative samples collected from the bauxite profiles and the underlying carbonates are summarized in Table 1 (Al-Ani, 1996).

Table 1: Major and minor elements in bauxite facies and in the source rocks
(Al-Ani, 1996)

Oxides/ elements	Kaolinitic bauxite	Separated pisolites of bauxite	Bauxitic Kaolinite	Iron-rich Bauxite	Flint Clay	Source rock	
						for bauxite	for Fe-bauxite
Wt.%							
SiO ₂	23.7	10	37.3	23.4	42.8	44.4	38.6
Al ₂ O ₃	53.1	62	44.6	42.3	37.4	34.4	32.7
Fe ₂ O ₃	1.1	1.6	1.3	16.4	1.5	3.5	5.6
TiO ₂	3.2	2.3	2.6	2.3	2.6	2.5	1.8
CaO	0.4	0.4	0.4	0.8	0.3	0.5	1
MgO	0.15	0.16	0.16	0.15	0.15	0.25	0.2
L.O.I	16.5	20.2	14.7	14.7	13.7	13	13.5
ppm							
Zn	53	89	68	38	80	93	155
Co	28	23	38	28	48	51	40
Ni	55	27	63	52	69	50	61
Ba	23	16	33	65	72	82	83
Mn	14	15	14	23	30	53	59
Cr	203	296	196	295	193	190	235
Cu	14	7	17	76	19	22	78
Sr	48	64	84	48	89	125	67
Zr	179	66	116	239	100	61	98
Ki	0.45	0.16	0.84	0.55	1.14	1.29	1.18
Rw	0.44	0.16	0.81	0.40	1.10	1.17	0.93

▪ Major element geochemistry

The bauxite deposits are mainly composed of four major oxides: Al₂O₃, Fe₂O₃, TiO₂ and SiO₂ (Table 1). The allochthonous lithofacies (claystone and mudstone) have the highest

silica values (44.4 and 38.6 wt.%, respectively), while the silica content of the autochthonous lithofacies (kaolinitic bauxite, bauxitic kaolinite, iron-rich bauxite, and flint clay) are 23.7, 37.3, 23.4 and 42.8 wt.% respectively (Table 1). The alumina content is highest in the kaolinitic bauxite facies (53.1 wt.% Al_2O_3), whereas the average values in the other autochthonous facies are 44.6, 42.3 and 37.4 wt.% in bauxitic kaolinites, iron-rich bauxites and flint clay respectively (Table 1).

The iron content is variable in different parts of the bauxitic profile; the average contents of Fe_2O_3 in kaolinitic bauxite, bauxitic kaolinite and flint clay are 1.1, 1.3 and 1.5 wt.% Fe_2O_3 respectively, but iron-rich bauxite obviously has the highest iron values with average of 16.4 wt.% Fe_2O_3 (Table 1). The average content of iron in the allochthonous lithofacies are 3.5 wt.% Fe_2O_3 in the claystone facies and 5.6 wt.% Fe_2O_3 in the mudstone facies (Table 1). The chemical indices of alteration ($\text{Ki} = \text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{Rw} = \text{SiO}_2/\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$), in the autochthonous lithofacies (kaolinitic bauxite, iron-rich bauxite, bauxite kaolinite and flint clay) have average contents of 0.44, 0.40, 0.81 and 1.10 respectively (Table 1 and Fig.8). Measurement of the vertical distribution of crystallinity index of kaolinite (KCI), $\text{Ki} = \text{SiO}_2/\text{Al}_2\text{O}_3$, $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios, TiO_2 value, and mineral composition through the bauxite profile shows large variations in their concentrations. Leaching and chemical weathering predominated in the upper part of the bauxitic profile, indicated by significant increase in the $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio, TiO_2 content and crystallinity index of kaolinite (KCI), in the middle parts of the bauxite profiles (Fig.8). The chemical variance within the bauxite profiles between bauxite samples compared with values in the source rocks may be ascribed to intense chemical weathering during the bauxitization process.

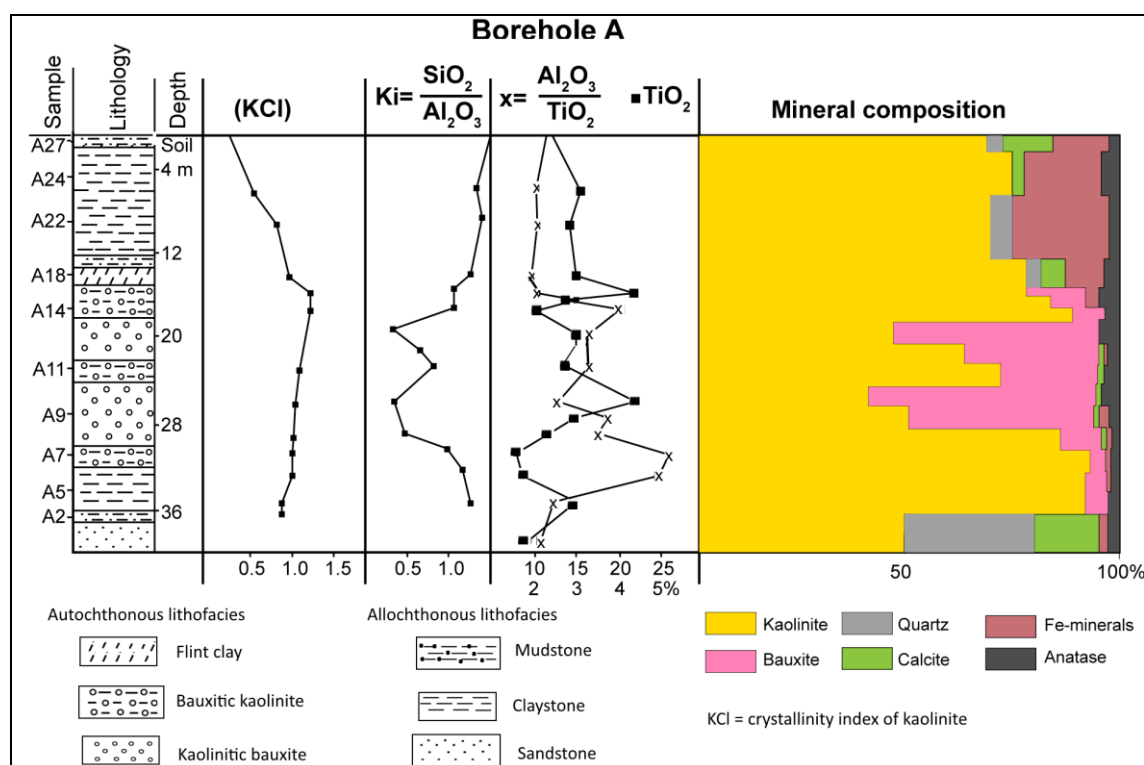


Fig.8: Vertical variation in the crystallinity index of kaolinite (KCI), $\text{SiO}_2/\text{Al}_2\text{O}_3$, $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios, TiO_2 content, and mineral composition within the bauxite profile of borehole A in North Hussainiyat karst bauxites (Al-Ani, 1996 and 2017)

Using ternary plots of Al_2O_3 – Fe_2O_3 – SiO_2 (Aleva, 1994) unveils some important points concerning the chemical characteristics of the bauxite ores. The North Hussainiyat karst bauxite data points on these plots show that the ores have bauxite to kaolinitic bauxite compositions with few samples in buaxitic kaolinite field and laterite (Fig.9). Plots of the bauxite data on the Al_2O_3 – Fe_2O_3 – SiO_2 triangular diagram illustrate different degrees of the bauxitization (Schellmann, 1986). In this diagram, Al_2O_3 -rich samples indicate higher degrees of bauxitization, while SiO_2 -rich samples indicate a weaker degree of bauxitization (Meyer *et al.*, 2002). In addition, the samples show that the karst bauxite deposits were the product of moderate to strong bauxitization.

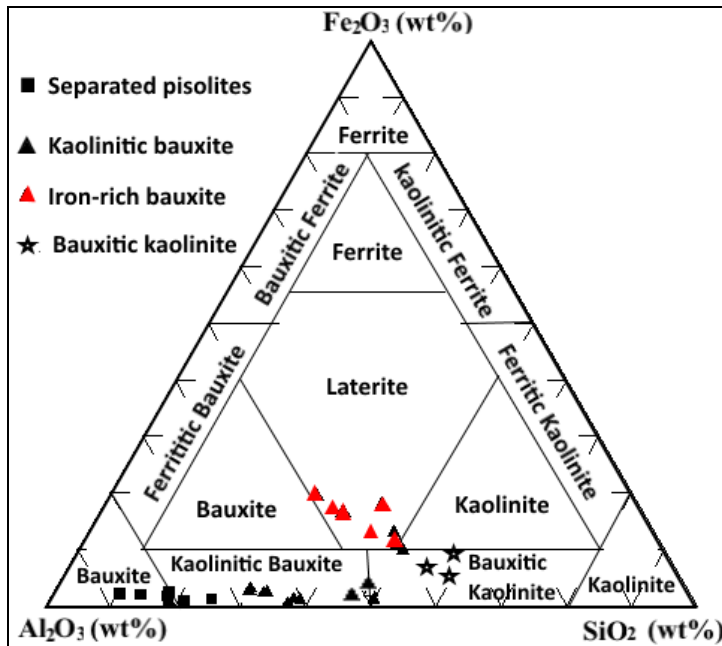


Fig.9: The Fe_2O_3 – Al_2O_3 – SiO_2 triangular diagrams showing the mineralogical classification of the bauxite ores (after Aleva 1994) and the position of the North Hussainiyat karst bauxites

▪ Trace element geochemistry

The bauxite ores are enriched in Zr, Cr and Ni relative to the overlying kaolinite. The bauxite lithofacies contain Zr (179 ppm), (116 ppm), (239 ppm) and (100 ppm), in kaolinitic bauxite, bauxitic kaolinite, iron-rich bauxite and flint clay respectively (Table 1). To identify parent rocks, elements that behave as immobile during bauxitization need to be detected. The chemical features of the chemical elements are responsible for retention or removal (immobile or mobile) of elements during the bauxitization process (Bárdossy, 1982; MacLean *et al.*, 1997). Studies show that some elements such as Si, Fe, Mg, K, Na and Sr do not form stable secondary minerals and are chiefly lost from the bauxite horizon, while some trace elements such as Zr, Ti, Ni, and Cr are considered to be immobile elements during weathering and bauxitization processes (Andrews *et al.*, 2001; Calagari and Abedini, 2007; Karadag~ *et al.*, 2009; Zarasvandi *et al.*, 2010; Babechuk *et al.*, 2014; Yu *et al.*, 2014; Zamanian *et al.*, 2016). Moreover, Mongelli *et al.* (2014) and MacLean *et al.* (1997) suggested that the immobile elements can even be used to trace the source of aluminum to a particular rock type or unit. In the Cr vs Ni diagram, the composition of the Hussainiyat bauxite samples is compared to the other Mediterranean karst bauxites (Fig.10a). They are similar to bauxite deposits in Turkey and Iran, but not to bauxite deposits in Greece and Apulian. Bivariate plots of Cr and Ni concentrations (e.g. Schroll and Sauer, 1968; Valetton *et al.*, 1987) were employed to characterize the bauxite samples of the North Hussainiyat bauxites (Fig.10b). Although the geochemical data suggest basalt as the main composition of their parent material, there is no

direct field evidence for basalt of comparative age or older in the Hussainiyat basin and in the surrounding areas. The plots stretch from the karst bauxite region and close to the high iron lateritic bauxite field (Fig.10b), suggesting a mixture of weathering products of a wide range of rocks. The low-iron bauxite specimens plot at karstic bauxite field and are close to the shale and slate parent rocks, whereas the iron-rich bauxite samples are located in the karstic bauxite field and are close to the basalt parent rock. The shale and slate here are collectively referred to as claystone and mudstone source rocks from which the bauxite raw material was derived.

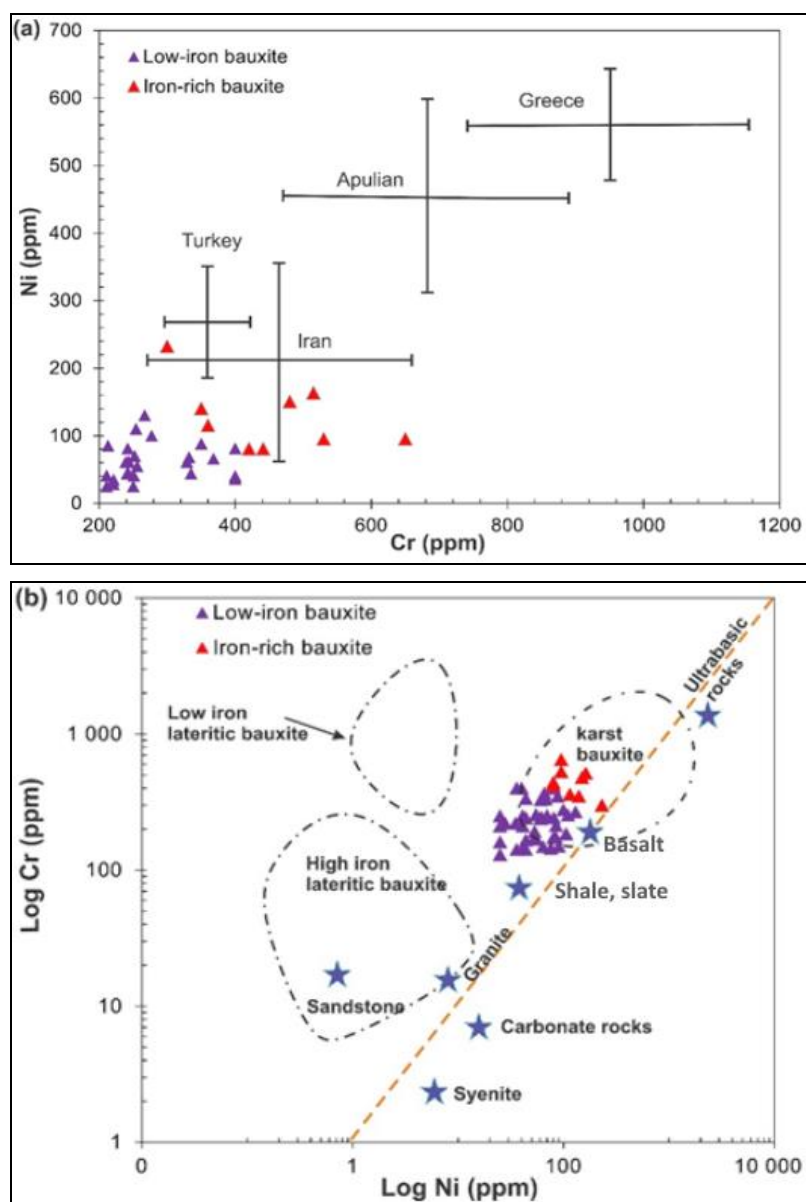


Fig.10: **a)** Binary diagram of Cr vs Ni showing the composition of the studied karst bauxite samples relative to other Mediterranean karst bauxite deposits represented as average value and standard deviation. Turkey: Ozturk *et al.* (2002); Greece: Campania: Mondillo *et al.* (2011); Apulian: Mongelli *et al.* (2014); and Iran: Zamanian *et al.* (2016). **b)** Binary diagram of Cr vs Ni log concentration values for potential precursor rocks (after Schroll and Sauer, 1968), showing the bauxite deposits data plot mainly in the karst bauxite field

The average concentration and depletion ratios were calculated with respect to the ratio between the content of an element in any given bauxitic facies (Cb) and kaolinite (Ck), as a source rock for the bauxite ore (Table 2). Most of the studied bauxite samples are enriched in the immobile elements (Al, Zr, Ti, Cr) and depleted in the mobile elements Ca, Mg, Si, Cu, Zn, Co, Sr, Ba, and Mn. Zirconium was enriched more than Al in all bauxite lithofacies. Low-iron bauxitic lithofacies, which include kaolinitic bauxite, bauxitic kaolinite and flint clay may have been formed under reducing conditions which caused Al enrichment and removal of Fe ($Cb/Ck = 0.31, 0.40$ and 0.43 , respectively) from kaolinitic sediments to form the white colour bauxite with some plant debris. The iron-rich bauxite lithofacies, indicate formation under oxidation conditions and leading to the enrichment of iron. The enrichment values of Zr in the kaolinitic bauxite and iron-rich bauxite ($Cb/Ck = 2.93$ and 2.44 , respectively) are higher than those of the bauxitic kaolinite and flint-clay facies ($Cb/Ck = 1.88$ and 1.74 , respectively). Nickel is more enriched than Al in bauxitic kaolinite and flint clay facies ($Cb/Ck = 1.26$ and 1.38 , respectively), whereas in kaolinitic bauxite Ni is less enriched than Al ($Cb/Ck = 1.1$) and depleted in the iron-rich bauxite facies (Cb/Ck ratio = 0.85). Although alumina is the main chemical component of bauxite, its enrichment relative to the parent rock is more restricted than that of Zr (such as in bauxitic kaolinite and flint clay facies; Table 2). Some trace elements were depleted during the bauxitization process. This represents a little leaching of the initial silica especially in the bauxitic kaolinite ($Cb/Ck = 0.84$) and flint clay facies ($Cb/Ck = 0.93$) and leaching of significant amount of silica from the kaolinitic bauxite ($Cb/Ck = 0.53$) and iron-rich bauxite ($Cb/Ck = 0.23$).

Table 2: Average concentration ratios (Cb/Ck) of major and minor elements in the autochthonous facies compared with kaolinite source rocks. Enriched elements ($Cb/Ck > 1$) and depleted elements ($Cb/Ck < 1$)

	Elementes	Kaolinitic Bauxite	Iron-rich Bauxite	Bauxitic Kaolinite	Flint Clay
Enriched > Al	Zr	2.93	2.44	1.88	1.74
	Al	1.54	1.32		
Enriched < Al	Ni	1.1	0.85	1.26	1.38
				1.21	1.1
	Ti	1.31	1.3	1.05	1.04
	Cr	1.07	1.32	1.03	1.02
	H ₂ O	1.3	1.05	1.13	1.05
Depleted	Fe	0.31	1.80	0.40	0.43
	Ca	0.81	0.80	0.66	0.63
	Mg	0.60	0.64	0.60	0.60
	Si	0.53	0.23	0.84	0.93
	Cu	0.63	0.92	0.77	0.86
	Zn	0.56	0.25	0.73	0.86
	Co	0.54	0.70	0.74	0.94
	Sr	0.40	0.65	0.27	0.71
	Ba	0.28	0.78	0.40	0.87
	Mn	0.22	0.4	0.26	0.5

ORIGIN AND FORMATION OF THE NORTH HUSSAINIYAT KARST BAUXITE

The origin of the North Hussainiyat karst bauxites has been discussed by several authors (e.g. Al-Ani, 1996; Mustafa and Jibrail, 1996; Al-Atia and Sa'adallah, 1996; Al-Bassam, 2005; Al-Ani, 2017). It is agreed that a considerable amount of material must have been eroded from the weathered granitic and metamorphic complexes of the Arabian Shield as well as from the pre-Jurassic sediments. These rocks were decomposed in humid tropical condition to form laterite and transported by streams and rivers. Considering the mineral associations and their phase changes in the bauxite ores, and the geological setting of the Hussainiyat area, a model was proposed by Al-Ani (1996 and 2017) for the bauxite-forming processes of the karst-fill deposits in the Hussainiyat area. The subareal exposure of the carbonate surface of the Ubaid Formation since the Late Cretaceous is attributed to marine regression. Subsequent activity of ground water produced a series of karst depressions where the rocks were removed by dissolution, forming underground voids. Where these underground voids have collapsed, a closed depression, or sinkhole, is formed at the carbonate surface (Fig.11a and b). The clastic detritus derived from the Lower Member of the Hussainiyat Formation was distributed over the coastal plain by alluvial processes, and the karstic depressions were gradually filled. The stream water flowing from NW to SE, away from the hills and/or ridges of the clastic member of the Hussainiyat Formation had transported the weathering products to karst depressions. Limestones of Ubaid Formation, forming the karst surfaces, are generally porous and they acted as a filter, retaining most of the accumulated residues. Collapse sinkholes form when the limestone is dissolved away from below, removing the support for the surface. Sinkholes filled with water also acted as traps for the accumulation of aluminous sediments. The sinkhole bottoms became swamps in which active leaching by ground water took place under reducing conditions (Fig.11b and c).

Continuing activity of ground water in dissolving the limestone of the karst depressions below the clays would cause slumping in the clays, thus facilitating the movement of ground water through the central part of clay deposits. The general condition of a humid tropical climate with a sufficient drainage resulted in dissolving almost all cations such as Ca, Mg, Na, K and much of the silica and iron by the ground water, leaving aluminum oxides and hydroxides. Thus a gradual transformation of the allochthonous detritus within karst depression to autochthonous bauxite products of chemical weathering is brought about (Fig.11d).

On the basis of mineralogy, texture, chemical and physical properties, the studied bauxite deposits contain many attributes which indicate that the weathered clastics of the Lower Member of the Hussainiyat Formation are the source rocks from which the bauxites were derived. The evidence includes the presence of kaolinite extraclasts from this unit scattered within the flint clay and karst bauxite deposits. This suggestion is supported by the similarity in molecular ratio $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{SiO}_2/\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3$ between allochthonous lithofacies within the bauxite profiles (unaltered claystone and mudstone), and the claystone of the Lower Member of the Hussainiyat Formation. Such genetic relationship suggests only a short transport and rapid deposition from source area to the karst environments.

The intensity of observed chemical weathering varies from one karst depression to another, being most intense in those which contain bauxite deposits (Fig.11e). This may be reflected by the increased development of the autochthonous units. Within the highly permeable karstic terrain, aggressive leaching gives rise to bauxite and high-alumina flint clays. Flint-clay is an intermediate phase between kaolinite of the source rock and bauxite minerals in karst depressions. It is inferred that parent kaolinitic clay colloids were

transported into the karst environments and there underwent further dialysis, alteration, and eventual crystallization in situ, producing a notably homogeneous kaolinite clay possessing interlocking crystallinity.

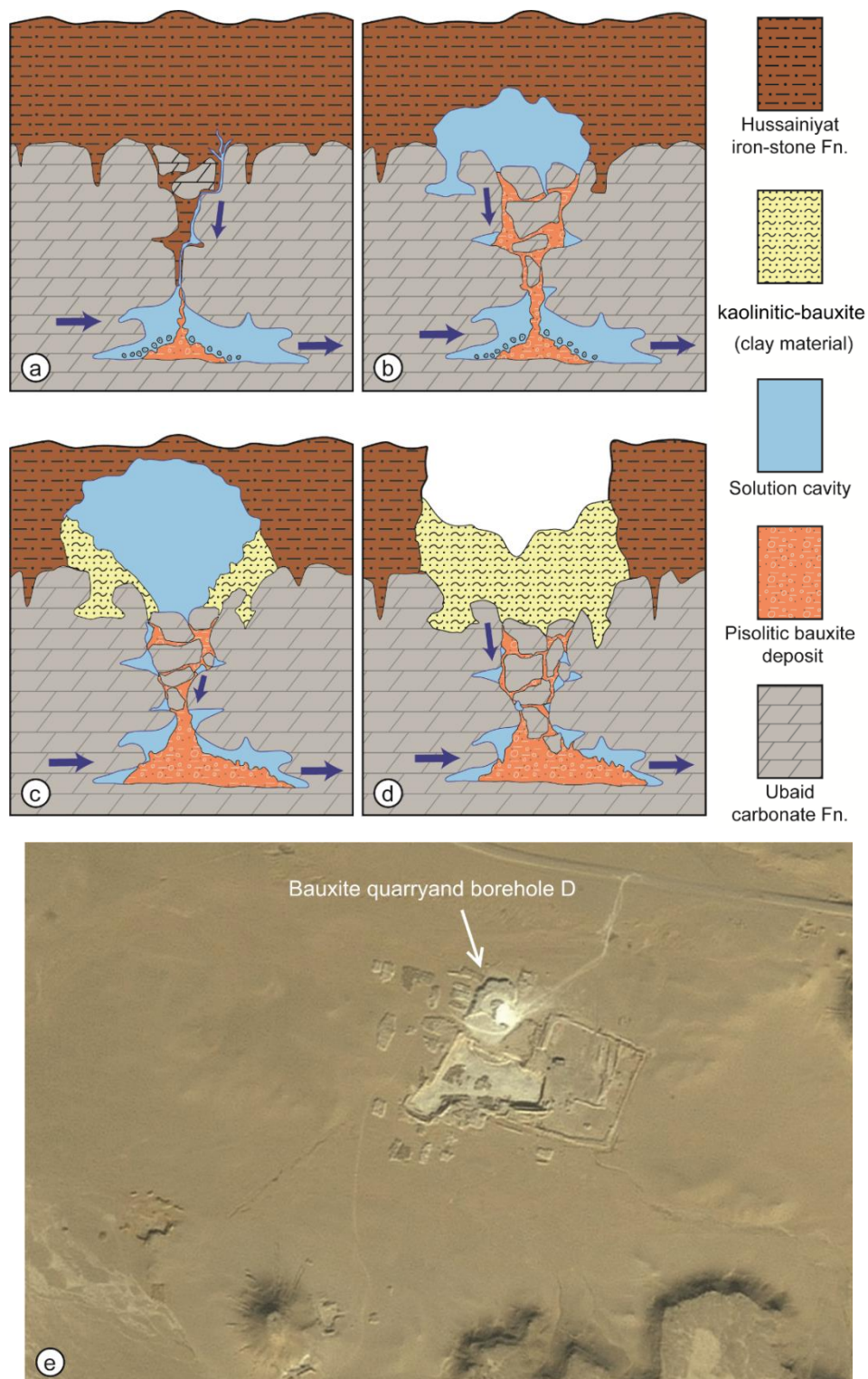
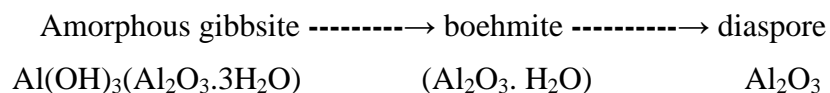


Fig.11: **a – d)** Schematic diagrams illustrating stages and processes of bauxitization and phase transformation in the studied bauxite deposit. **e)** Google earth image showing the bauxite quarry and collapse sinkholes in the Hussainiyat area, Western desert of Iraq

MINERAL GENESIS

The genesis and relationship among various minerals in the karst bauxites reflect all the chemical effects during the entire ore-forming process. Varied and occasionally contradictory, mineralogical transformations can be found in different bauxite deposits (Bárdossy, 1982). The depositional environment of the North Hussainiyat karst bauxite deposits in the Western Desert of Iraq has been discussed by Al-Ani (1996 and 2017), Al-Atia and Sa'adalla, (1996) and Al-Bassam (1996 and 2005). Boehmite and gibbsite are the only bauxite minerals found in these bauxites; most of bauxite profiles in some locations, such as A, V61, D, B13 (Fig.1) are characterized by an upper boehmite zone, overlying a gibbsite – boehmite zone. It seems that, like many other boehmitic bauxite deposits, the original mineralogical composition of the studied karst bauxite appears to have been gibbsitic, which was transformed from clay minerals (kaolinite) during karstification and intense chemical weathering processes (Bárdossy and Aleva, 1990; Horbe and Anand, 2011).

According to Maynard (1983), boehmite forms in the zone of leaching (above the water table) and gibbsite in the zone of saturation (below the water table). Field observations and experimental studies conclude that amorphous aluminum hydroxide or gibbsite (primary bauxite) can form directly from kaolinite after removing of silica. Kaolinite dissolves incongruently to give gibbsite (as residue material) and amorphous silica (as aqueous) in solution. Afterward boehmite forms from gibbsite in the temperature range of 35 – 50 °C, due to water loss (dehydration) during compaction (Valeton *et al.*, 1987; Temur and Kansun, 2006). Kittrick (1969) came to the same conclusion and suggested that there is an aging dehydration relationship of the alumina phases as follows:



Mineralogical and petrographic investigations (Al-Ani, 2017) revealed that most boehmites (low iron bauxite) are characterized by a coarse to medium particle size (collomorphic-fluidal, pisolitic, oolitic, nodular, brecciated, and skeletal textures) (Figs.7a – d) and a high crystallinity degree (Fig.6), while high-iron bauxite characterized by a small particle size (collomorphic-fluidal, oolitic) and low degrees of crystallinity (Figs.7e – h). These features indicate an authigenic origin of the North Hussainiyat karst bauxite deposits. Low iron bauxite of the studied karst depressions may have been formed under reducing conditions which caused Al enrichment and the removal of Fe from kaolinitic sediments to form the white colour bauxite with some plant debris.

The presence of anatase in bauxitic horizons generally suggests reducing conditions during formation of the karst bauxite deposits. The iron-rich bauxite of the karst depressions, indicate formation under oxidation conditions. Goethite and hematite are the major iron oxides in the North Hussainiyat karst bauxites and their occurrences in the matrix are not syngenetic and suggest that they formed in different Eh and pH conditions. Schorin and Puchelt (1987), concluded that the red bauxites were deposited on land, under oxidizing conditions in temporary fresh water basins.

According to the formation conditions of the major minerals in karst-type bauxite presented by Temur and Kansun (2006); Liu *et al.* (2012 and 2013); Ling *et al.* (2015) and Zamanian *et al.* (2016), the studied bauxite deposit formed in an environment ranging from acidic-oxidizing to basic-reducing water conditions. The grain size of diagenetic and detrital particles (such as pisoids, ooids and intraclasts) vary from several microns to several

millimeters. The heterogeneous presence of ooids and pisoids within the bauxite ore can be attributed to the original heterogeneity of colloids that originated from the alteration and weathering of parent rocks.

BAUXITE RESOURCES AND INDUSTRIAL APPLICATIONS

Since its discovery in 1991, the North Hussainiyat karst bauxite deposits gained increasing interest from the Iraqi industry. The bauxite reserves were estimated together with the associated flint clay deposits in several karst depressions (Mustafa *et al.*, 1991; 1993; 1994 and 1996). The bauxite reserves were estimated (until 2003) by 1.28 m.t.; out of which 0.16 m.t has been mined and exploited, and the flint-clay reserves were estimated by 9.51 m.t; out of which 0.29 m.t has been exploited. The quality of the bauxite reserves ranges from low quality bauxite to kaolinitic bauxite. Some bauxitic kaolinites were also included in these reserves. The grade was reported as Al_2O_3 content ranges from 43.9 – 56.27 wt.%; SiO_2 21.0 – 26.0 wt.%; Fe_2O_3 0.72 – 14.86 wt.% and TiO_2 1.6 – 2.82 wt.% (Mustafa *et al.*, 1993). In view of the small amount of the reserves, difficult mining conditions and the poor quality of the bauxite, being low in alumina and high in silica, these deposits have been only used in the production of refractories (Muslet, 1996) and alum (Al-Rubai, 1996). Experimental studies in Iraq Geological Survey, however, have shown the possibility of extracting alumina from the North Hussainiyat bauxites (Hammoudi, 1996) and from the flint and flint-clay to prepare poly-aluminum chloride for water treatment (Jassim and Abood, 2005). In recent studies these bauxites became the target of research work to extract titania (Moayyad G. Jalhoom, University of Technology, Baghdad, personal communication).

The prospect of finding karst bauxites in older rock units have been found promising by Al-Bassam *et al.* (1998 and 2005). Subsurface karst bauxites are expected in the carbonate units of the Upper Triassic Mulussa Formation and Zor Hauran Formation in the area SW of the Hussainiyat karstified area (south of Rutba-Amman highway), lying below Cretaceous and Paleogene sedimentary cover. In these areas maximum lineament intersection density has been recorded by LANDSAT image analysis (Al-Amiri, 1978). Kaolinitic source rocks were available in the Paleozoic units, especially in the Ga'ara Formation, which was exposed in the Triassic and Jurassic times north of Rutba-Amman highway. Favorable climatic conditions existed sometimes in the Late Triassic and Early Jurassic with clear evidence of a major event of chemical weathering at the end of the Triassic and Early Jurassic in the Arabian Plate (Abed, 1979; Goldbery, 1979 and Valetton *et al.*, 1983).

The prospects of finding stratiform bauxite deposits in exposed Jurassic and/or Cretaceous formations was found not encouraging (Al-Azzawi and Dawood, 1996). However, the potential of discovering stratiform (unconformity) type bauxite deposits in subsurface have been discussed by Al-Bassam *et al.* (2005). The authors suggested the possibility of presence of this type of bauxite, which should be equivalent to that discovered in Zabira of Saudi Arabia, in the subsurface south of Rutba–Km 160 highway at the unconformity contact between Cretaceous and older units. The unconformity surface was subjected to weathering and erosion for more than 20 Ma under various climatic conditions; the Barremian – Albian stages are the most significant in this sense, having a rain-forest climate in Iraq and the neighboring areas according to palynological findings (Al-Amiri, 1994). Moreover, source rocks of suitable composition (kaolinitic claystones) were available in older rock units (Ga'ara, Hussainiyat and Amij formations), which were exposed in the Early Cretaceous time at topographically higher positions. Shallow grabens, proved by geophysical survey to be present at the pre-Cretaceous unconformity surface in the area south of the highway (Al-

Bassam *et al.*, 1998), may have served as ideal topographic traps for these bauxites and could have preserved the deposits from erosion.

CONCLUSIONS

The karst bauxites discovered in northern Hussainiyat area in the Ubaid Formation (Lower Jurassic) are the only bauxite resources in Iraq found yet. They are low-grade ores composed of boehmite and gibbsite in association with kaolinite and contain anatase and Fe-oxyhydroxides. The bauxite is pisolitic, ooidal and massive in texture and found in lenticular forms bound by kaolinitic clays and quartzose sandstone. They show enrichment in the immobile elements Al, Ti, Zr and Cr and depletion of Si, Ca, Mg, Fe, Sr and other mobile elements. The age of these karst deposits is controversial between Lower Cretaceous, Lower Jurassic and Eocene. The parent rocks are believed to be the kaolinitic claystones of the Hussainiyat Formation (Lower Jurassic). The reserves have been estimated by about 1.28 m.t. with Al_2O_3 content ranges from 43.9 – 56.27 wt.%; SiO_2 21.0 – 26.0 wt.%; Fe_2O_3 0.72 – 14.86 wt.% and TiO_2 1.6 – 2.82 wt.%. There is a fairly good possibility of locating further karst bauxites in the Mulussa and Zor Hauran formations (Triassic) and stratiform bauxite at the Cretaceous–Jurassic subsurface contact south of the Rutba–Km 160 highway. The North Hussainiyat karst bauxites were partly exploited industrially for alum production and refractories and experimentally for alumina extraction.

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