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MINERAL DEPOSITS AND OCCURRENCES OF THE LOW FOLDED ZONE

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ABSTRACT

The Low Folded Zone of Iraq is rich in a variety of mineral resources and industrial rocks, developed over the history of Paleogene and Neogene marine and non-marine depositional processes. The Fatha Formation (Middle Miocene) is the most important minerogenic rock unit in this zone. Native sulfur is the remarkable mineral resource; the identified sulfur resources are the largest of its kind in the world. Raw materials for cement industry are present in sufficient quantities, as well as gypsum and gravel – sand aggregates. Rock salt deposits in the center of two main Early and Middle Miocene evaporitic basins were intersected in several wells in considerable thicknesses within the Dhiban and Fatha formations.

Interesting deposits of bentonite "sensu stricto" were identified, as well as occurrences of palygorskite, phosphate and Fe-oxyhydroxides (after pyrite). Paleogeography, tectonic settings and climatic conditions were important factors in the development of primary syngenetic deposits such as limestone, gypsum and rock salt in addition to some phosphate occurrences. Whereas, biochemical and chemical epigenetic alterations were important factors in the development of some other mineral deposits located in the Low Folded Zone, such as native sulfur and bentonite, together with some mineral occurrences including palygorskite and Fe-oxyhydroxides.

الرواسب والشواهد المعدنية في نطاق الطيات الواطئة

خلدون صبحي البصام

المستخلص

تتناول هذه الورقة المصادر المعدنية والصخور الصناعية في نطاق الطيات الواطئة الذي يحتوي على رواسب متنوعة تكونت عبر التاريخ الجيولوجي للمنطقة خلال عصري الپاليوجين والنيوجين في بيئات بحرية وقارية مختلفة. يمكن اعتبار تكوين الفتحة (المايوسين الأوسط) أهم التكوينات الجيولوجية من الناحية التمعدنية في هذا النطاق لتنوع مصادره المعدنية وأهميتها الصناعية والاقتصادية.

تمثل رواسب الكبريت الحر أهم المصادر المعدنية في نطاق الطيات الواطئة التي تم التثبت منها ودراستها في أكثر من حقل معدني وتمتد من اللزاگة إلى الفتحة مرورا بحقل المشراق المعروف ومعظم التراكيب الجيولوجية المحدبة في المنطقة. تعتبر احتياطيات الكبريت الحر في هذا النطاق الأكبر حجما من نوعها في العالم. تتوفر إضافة إلى ذلك مصادر وافية من المواد الأولية الصالحة لصناعة الاسمنت وهي حجر الكلس والأطيان فضلا عن الجبس ورواسب الحصى والرمال وجميعها مصادر مهمة لمواد البناء. اكتشفت رواسب مهمة من الملح الصخري في رواسب المايوسين المبكر والأوسط في مراكز أحواض رسوبية تبخرية أهمها موجود في منطقة سنجار ويمتد إلى داخل سوريا ومنطقة جنوب كركوك وحمرين الجنوبي. تتميز هذه الرواسب الملحية التي اكتشفت في رواسب تحت السطح بسمك عالي ونقاوة جيدة ضمن تكويني الذبان والفتحة.

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تم اكتشاف عدة رواسب وشواهد معدنية ذات أهمية علمية في نطاق الطيات الواطئة هي البنتونايت في تكوين المقدادية المتكون من تحول الرماد البركاني والباليغورسكايت في تكوين إنجانة المتكون بالترسيب المباشر في شقوق وتكسرات حدثت بالتزامن مع الترسيب والفوسفات في سطح عدم التوافق بين تكويني جدالة وإبراهيم ويمثل ترسيب بحري يمكن مقارنته برواسب فوسفاتية من نفس العمر (الإيوسين الأوسط) في غرب العراق والدول المجاورة وشواهد من أكاسيد الحديد الناتجة عن تأكسد البايرايت في مكاشف وسطوح تكوينات مختلفة وتحت ظروف مناخية رطبة نسبيا في منطقة سنجار.

ساهمت عدة عوامل في تكوين وتطور الرواسب والشواهد المعدنية في نطاق الطيات الواطئة أهمها الجغرافية القديمة للمنطقة خلال الباليوجين والنيوجين والتي تحكمت بالسحنات الرسوبية فضلا عن الظروف المناخية التي سادها الجفاف خلال تلك الفترة. أسهمت تلك العوامل في نشوء عدة رواسب معدنية مهمة منها الأملاح والجبس وحجر الكلس وشواهد الفوسفات، في حين أسهمت عوامل جيولوجية أخرى حدثت بعد الترسيب في نشوء خامات معدنية من نوع آخر أهمها الكبريت الحر من تحول الجبس بعمليات اختزال وأكسدة وبوجود رواسب هيدروكاربونية وحركة مياه جوفية نشطة وتوفر المكمن التركيبي المناسب. ومنها أيضا البنتونايت المتكون من تحول الرماد البركاني وشواهد أكاسيد الحديد التي تكونت من أكسدة البايرايت الموجود بوفرة في عدة تكوينات في جبل سنجار.

INTRODUCTION

▪ General Geology and Paleogeography

The Low Folded Zone (Fig.1) is mostly covered by Neogene formations; mainly Fatha (Middle Miocene), Injana (Late Miocene), Mukdadiya (Late Miocene – Pliocene) and Bai Hassan (Pliocene – Pleistocene). Neogene clastic rock units, sometimes with anhydrite and carbonates, fill the synclinal plains in the SE. In the NW part, Early and Middle Miocene carbonates and anhydrites form the core of short anticlines. The prominent structures of Sinjar and Qara Chouq are generally built by Paleogene carbonates (Jassim and Buday, 2006).

The area was the depocenter of the Neogene molasses. It was a subsiding area throughout the Mesozoic, Paleogene and Neogene (Jassim and Buday, 2006). The paleogeographic facies configuration was described by Buday (1980) as follows:

Oligocene: Area of no deposition (or erosion) in the north, neretic (reef – forereef) in the southern and northern flanks of the basin and basinal facies in the center.

Early Miocene: Evaporites (Dhiban Formation) in the middle and carbonaceous marine rocks without evaporites (Euphrates Formation) in the flanks of the depositional basin.

Middle Miocene: Lagoonal evaporitic deposition (Fatha Formation) in most of the area.

Late Miocene – Pleistocene: Fluvial clastics, Bai Hassan Formation in the middle and Injana and Mukdadiya formations in the flanks of the basin.

▪ Minerogenic Characteristics

The area is characterized by the following mineral resources and industrial rocks: Native sulfur, limestone, dolostone, gypsum and rock salt (Fatha Formation), bentonite (Mukdadiya Formation) and gravel – sand aggregates (Bai Hassan Formation and Quaternary River Terraces and Alluvial Fans). Some interesting mineral showings were also recorded. They include iron oxyhydroxides (after pyrite) in several rock units exposed at Sinjar Anticline, phosphates associated with glauconite, at the unconformable contact between Jaddala (Late – Middle Eocene) and Ibrahim (Late Oligocene) formations in Sinjar Anticline, and palygorskite as epigenetic fracture-and vein-fill deposits in the Injana Formation of Ba'shiqa and Jabal Maqloub areas.

The area includes several minerogenic zones classified according to specific minerogenic processes (Al-Bassam, 2007) (Fig.2): Marine chemical and biochemical precipitation (limestone, dolostone and phosphate), evaporation in closed marine basins (gypsum and rock salt), alteration of volcanic ash (bentonite), pedogenic (epigenetic) alteration and precipitation (palygorskite and Fe-oxyhydroxides), mechanical precipitation in fluvial systems (gravel, sand and mud) and biochemical epigenetic alteration (native sulfur).

The results presented in this article are based on data and information provided by previous work of GEOSURV geologists. It represents about 50 years of geological survey and mineral exploration projects in the area. The data were obtained from GEOSURV reports and were compiled to present a condensed paper on mineral resources of the Low Folded Zone, as part of this special issue.

- **Previous Work**

The Low Folded Zone attracted the attention of early geological work in Iraq because of its enormous oil potential. Drilling for oil exploration covered most of the anticlinal structures in the area and revealed many interesting mineral showings.

Native sulfur showings were documented by the early geologists of the Site Investigation Company (Webber, 1952; Bolton, 1954; Paver, 1954 among others). The sulfur exploration was continued by the "Soviet" geologists in Mishraq and Lazzaga areas (Chebanenko and Toutevich, 1962). Iraqi geologists followed up the exploration work (Mansour and Al-Hadithi, 1967; Al-Mehaidi, 1970 and Al-Timimi, 1970). Other studies were carried out by Al-Sawaf, 1977; Abdul Hussain and Saib, 1977 and Barker *et al*., 1979). Extensive exploration projects for native sulfur were carried out by GEOSURV in the period 1986 – 1992 (Ma'ala *et al*., 1989; Jassim and Al-Murib, 1989; Al-Ka'aby *et al*., 1989; Jassim, 1991; Sharif *et al*., 1992; Fouad *et al*., 1992; Fouad, 2002; Fouad *et al*., 2004 and Yasin *et al*., 2007).

Exploration for raw materials for cement industry started as early as the fifties of the past century (Leitch, 1954). The work culminated in the seventies and eighties (Al-Murib, 1978, and 1980, Ameen, 1980; Al-Mubarak, 1980 among others). The geological survey of the area documented numerous limestone occurrences mostly in the Fatha Formation.

Similarly, gravel and sand aggregates received extensive work in the seventies and early eighties of the past century to meet the construction demands of the area (Al-Ka'aby and Al-Bayati, 1975; Al-Ka'aby, 1975 and 1977; Younan and Saib, 1976; Al-Hussain *et al*., 1976; Younan, 1980a and b; Al-Hussain and Saib, 1981 and Shafiq, 1981).

Gypsum, another construction raw material, was explored in the Fatha deposits extensively (Al-Ka'aby, 1977; Al-Ka'aby and Mohamad, 1976; Jargees, 1979; Touni, 1979 and 1980, Al-Ka'aby and Touni, 1979 among others). Rock salt beds were encountered in the Dhiban and Fatha formations. They were documented by oil geologists, but not as an exploration target. Rock salt deposits received more attention in the eighties of the past century as a possible underground storage potential (Etabi, 1978; Dimitrov *et al*., 1984 and Mustafa *et al*., 1984).

Bentonite exploration was made in Qara Tappa (Himreen Range) on the basis of old (historic) workings in the area. The deposit, together with neighboring Zarloukh, Tayawi and Emgarin deposits and occurrences were investigated in the seventies by GEOSURV geologists (Zainal and Jargees, 1972 and 1973 and Al-Maini, 1975). Palygorskite was discovered by the geologists of Mosul University (Al-Sayegh *et al*., 1976). Iron showings in Sinjar Anticline were noticed, documented and studied by GEOSURV geologists (Ma'ala, 2001 and Ahmed, 2009). Phosphates were observed and recorded by Al-Ani (2005) as part of an M.Sc. study in the University of Baghdad.

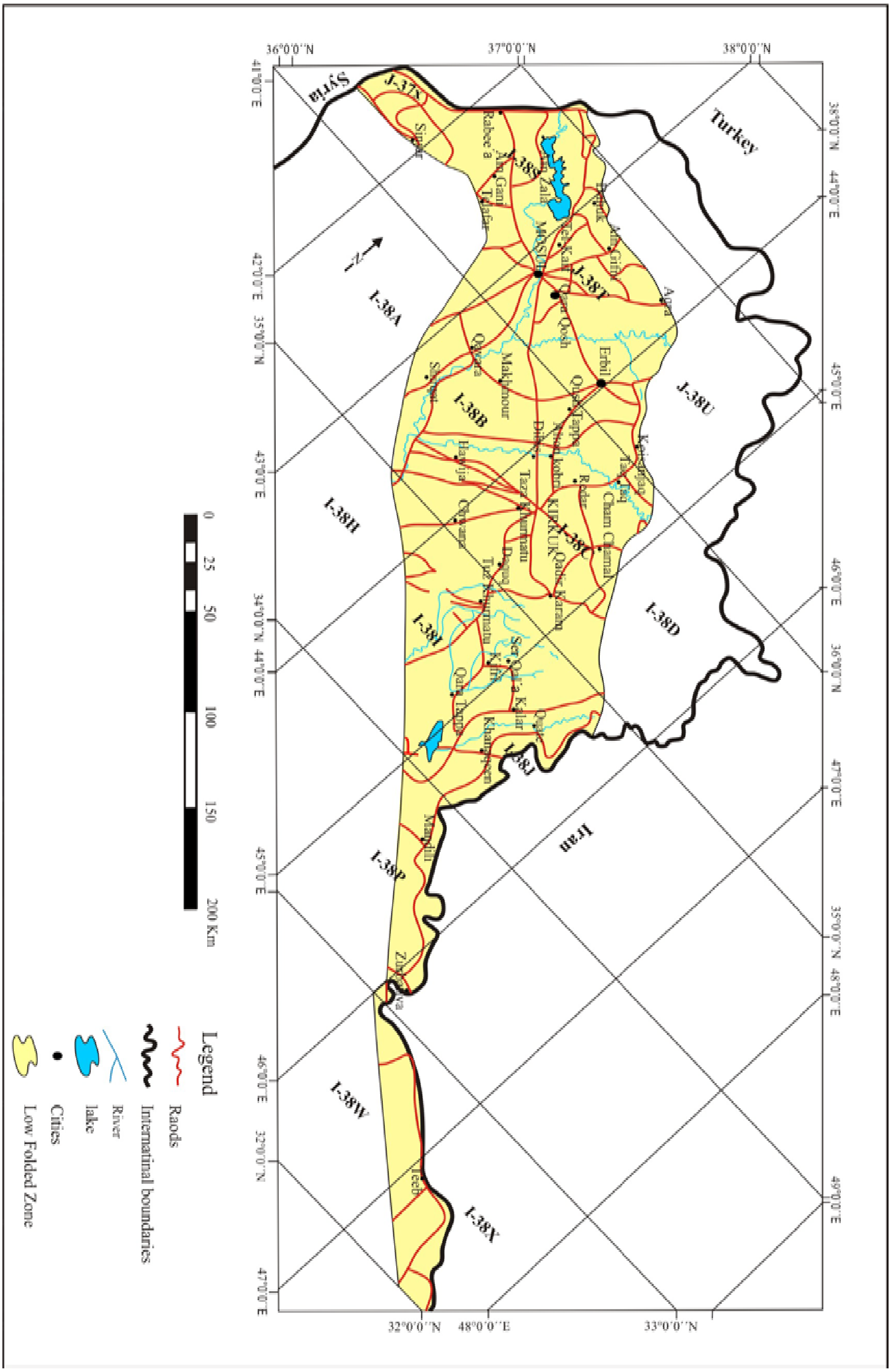

Fig.1: Location map of the Low Folded Zone

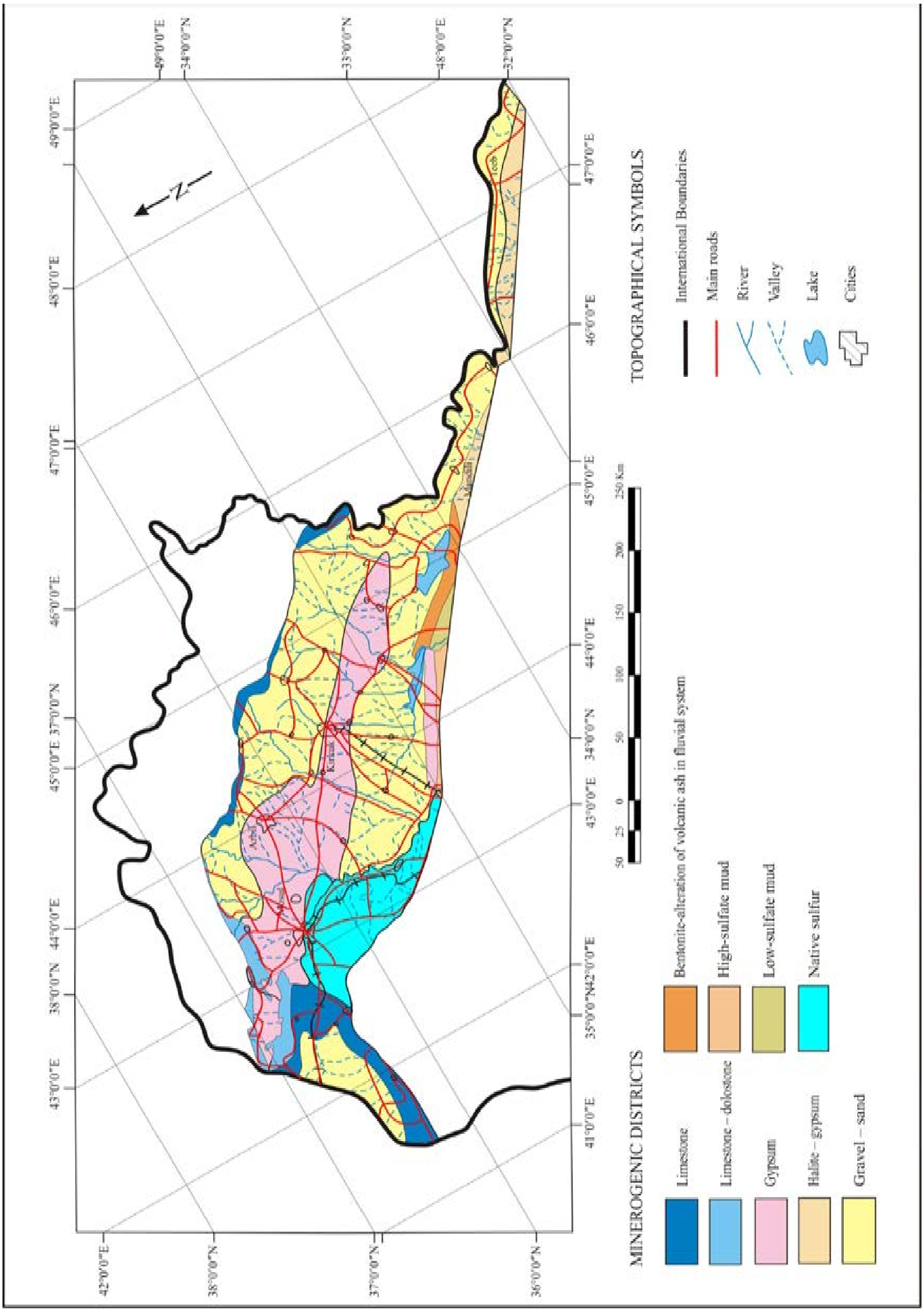

Fig.2: Minerogenic districts of the Low Folded Zone (Al-Bassam, 2007)

RESULTS: MINERAL RESOURCES AND MINERAL SHOWINGS

Mineral resources are those, which are found as deposits, whose geological extensions and specifications are understood and can be economically potential. On the other hand, mineral showings are occurrences of some minerals or industrial rocks of economic interest, but their mode of occurrence or the available information are not enough to consider them as deposits.

▪ Native Sulfur Deposits

They are confined to the Mosul – Fatha Minerogenic Zone and are the largest native sulfur deposits of their type in the world. They are found in three mineralization areas: Mishraq, Lazzaga and Fatha (Fig.3). They are stratigraphically controlled by the Lower Member of the Fatha Formation (Middle Miocene).

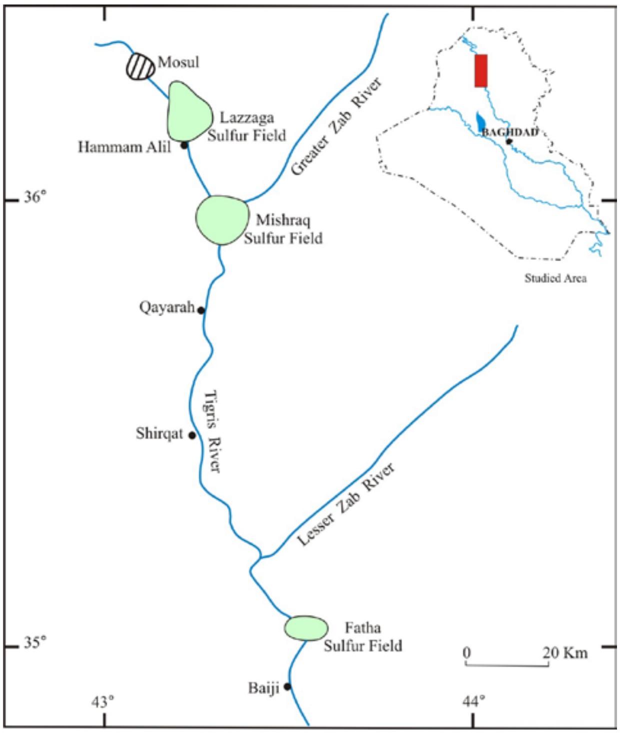

Fig.3: Location of main native sulfur mineralization fields

― Mishraq Deposits: The Mishraq deposits are located within a NW trending, double plunging anticline, about 11 Km long and 3.5 Km wide at surface. The structure is highly faulted and the highest intensity of faulting and folding is associated with the thickest sulfur accumulation (Barker *et al.*, 1979). The Mishraq structure has a complex and active hydrogeological conditions, due to faulting, folding and karstification of the Fatha Formation. Most of the groundwater is within vugs, joints fractures and cavities in limestones (Al-Sawaf, 1977). Six aquifers were recognized in M1 (Chebanenko and Toutevich, 1962). Water temperature is higher than normal with about (25 – 35) ºC, and rich in dissolved H_2S. Three sulfur-bearing horizons were identified in the Lower Member of the Fatha Formation.

Three mineralizing fields were investigated: M1 (present mine), M2 and M3. M1 is situated on the western bank of the Tigris River and covers about 9 Km^2. M2 is situated on the eastern bank, N of the Greater Zab River and covers about 5 Km^2. M3 is situated on the eastern bank south of the Gteater Zab River and covers about 7 Km^2.

The thickness of the sulfur-bearing horizons ranges from less than one meter to more than 40 m (average about 25 m) (Fig.4). The sulfur content varies from about 10% to about 50%. The overburden is generally more than 50 m.

The ore is present in various textures (Fig.5): Ribbon, drusy, pseudo brecciated, massive, nests and vein-fillings (Sharif *et al*., 1992). Two types were recognized by Chebanenko and Toutevich (1962); coarsely crystalline and fine crystalline sulfur. Both types are intimately associated with secondary calcite and bitumen. The total identified sulfur resource at the Mishraq field was estimated by about 570 m.t. in the three mineralizing centers (M1, M2 and M3) (Chebanenko and Toutevich, 1962; Al-Ka'aby *et al*., 1989; Jassim and Al-Murib, 1989 and Sharif *et al*., 1992).

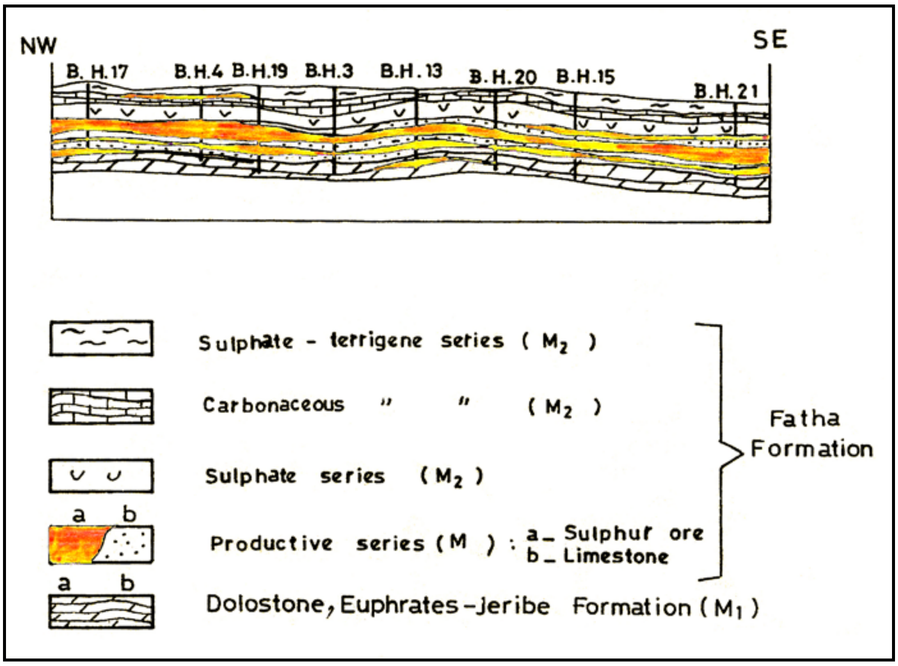

Fig.4: Geological cross section in the Mishraq (M1) sulfur deposit (Chebanenko and Toutevich, 1962)

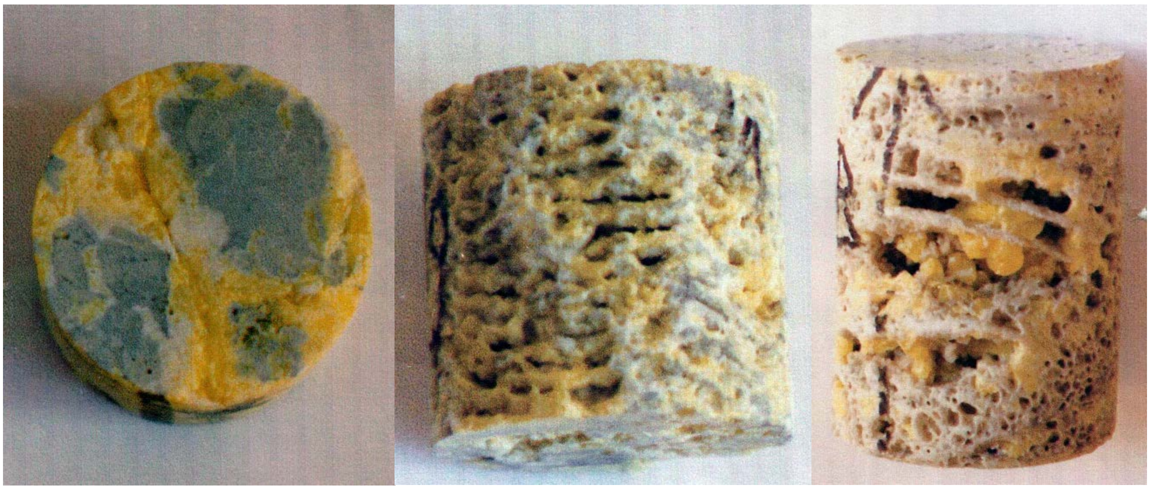

Fig.5: Various textures and structures of native sulfur in the Mishraq deposit (Ma'ala *et al*., 1989)

─ **Lazzaga Deposit:** It is located 15 Km south of Mosul city on both banks of the Tigris River and covers about 50 Km^2 in area. Six sulfur-bearing horizons were recognized within the Fatha Formation, ranging in thickness from 1.0 to 14.7 m and sulfur content ranges from (10 – 53) %. The overburden is sometimes thin (less than 50 m). The reserves were estimated in several stages (Al-Timimi *et al*., 1970; Jassim, 1991 and Yassin *et al*., 2007). The total indicated resources are about 310 m.t. in Lazzaga I, II and III.

─ **Fatha Deposit:** It is located west of the Tigris River, about 220 Km N of Baghdad. Four sulfur-bearing horizons were recognized in the Fatha Formation, all of which are composed of cavernous and bituminous limestones. Sulfur is rarely found in gypsum – anhydrite or claystone beds. The total thickness of the three identified sulfur-bearing horizons ranges from (2.5 – 55) m with an average sulfur content of about 35%. The total thickness of the overburden rocks ranges from (10 – 125) m and the identified sulfur resources were estimated by about 37 m.t. (Al-Mehaidi, 1970). In recent surveys, sulfur showings were documented and analyzed from outcrop sections. Three sulfur-bearing horizons were identified, total thickness is 15.8 m and sulfur content ranges from 12.9 to 78.4% (mean 44.0% S) (Fouad *et al*., 1992).

─ **Sulfur in Other Anticlinal Structures of Mosul Area:** These are a number of native sulfur showings located west of the Tigris River and were encountered during exploratory drilling for oil (Table 1). These sulfur showings were found in (1 – 4) horizons in the Fatha and Euphrates formations (?) bituminous carbonates. These deposits showing were considered as part of the sulfur resources of the Mosul – Fatha Zone and a total of about 134 m.t. of geological resources were estimated (Mansour and Al-Hadithi, 1967 and Abdul Hussain and Saib, 1977).

Table 1: Native sulfur occurrences in the Mosul area

Structure	No. of S-horizons	S (%)
Qayara	4	1 – 9.6
Najmah	3	1.8 – 30.0
Kasab	2	0.5 – 39.2
Jawan	3	3.7 – 37.5
Habbara	2	3.3 – 22.8
Qalian	3	8.5 – 20.6
Adayah	2	1.1
Ibrahim	1	1.6

▪ **Gypsum**

Iraq contains huge amounts of primary gypsum deposits, almost all of which are in the Middle Miocene Fatha Formation, exposed mainly in the Low Folded Zone. Usually more than ten thick gypsum horizons were recorded in this formation in alternation with claystone and limestone. The gypsum is found as nodular or bedded with (44 – 46) % SO_3, exposed at the flanks and plunges of anticlinal structures. Up to 20 m thick individual gypsum beds were recorded in the area (Mansour and Toma, 1983).

Several gypsum deposits have been explored in the Low Folded Zone with identified resources (reserves) of about 160 m.t. (Table 2). It is mainly used in the construction industry. All deposits are associated with anticlinal structures and consequently most gypsum beds are with a dip, reaching up to 50º as in Makhmour deposit. During the regional geological mapping of the Low Folded Zone more than 50 primary gypsum occurrences were documented, sampled and analyzed. All of which are in the Fatha Formation (Table 3).

Table 2: Chemical composition of gypsum deposits in the Low Folded Zone

Deposit	Formation	SO_3 (%)	CaO (%)	IR (%)	H_2O^+ (%)
Qara Walli	Fatha	45.5	31.4	1.2	20.0
Al-Qausiyat	Fatha	45.1	32.3	1.2	18.7
Makhmour	Fatha	44.5	32.2	2.0	18.1
Derbandi Bazian	Fatha	44.9	32.2	1.8	17.7
Ain Al-Nukhaila	Fatha	44.4	32.8	2.5	18.0
Sulaiman Beg	Fatha	44.9	32.4	0.8	18.8
Tarjil	Fatha	44.8	32.2	2.0	18.5
Al-Heshaimia	Fatha	44.7	32.2	n.a.	20.5
Al-Jabal	Fatha	44.2	32.1	n.a.	20.8

─ **Qara Walli:** 5 Km SE of Tel Afar, Zummar Anticline. Up to 20 m thick gypsum beds interbedded with marl, claystone and limestone (4.5 – 15 m thick). Resource were estimated by 100 m.t. (Al-Ka'aby and Muhamad, 1976) (Fig.6).

─ **Al-Qausiyat:** 7 Km NW of Mosul. Horizontal gypsum beds interbedded with claystone. Two beds were recognized, the upper is about 12 m thick with up to 9.7 m thick overburden (average 3 m). The lower is about 7 m thick with 3.5 m claystone overburden. Resources were estimated by 9.5 m.t. (Jargees, 1979).

─ **Makhmour:** Northern Dome of Qara Chouq structure, about 0.5 Km NE of Makhmour town. The strata dip (70 – 85)º in the SW limb and (35 – 55)º in the NE limb. More than 10 exposed gypsum beds in the Fatha Formation of various thicknesses were encountered. Resources were estimated by 7 m.t. (Al-Ka'aby, 1977).

─ **Derbandi Bazian:** 4 Km NW of Derbandi Bazian, three gypsum beds, (10 – 20) m in thickness, alternating with claystone and limestone. Resources were estimated by 9.3 m.t. (Touni, 1979).

─ **Ain Al-Nukhaila:** 40 Km NE of Tikrit. Two gypsum beds, 6 m and 7.6 m thick separated by claystone and marl intercalations. Resources were estimated by 9.9 m.t. (Ghalib, 1980).

─ **Sulaiman Beg:** 5 Km NE of Sulaiman Beg. Ten gypsum beds, (3 – 20) m thick alternating with marl and claystone interbeds. Resources were estimated by 21.4 m.t. (Touni, 1980).

─ **Tarjil:** 15 Km SE of Kirkuk, exposed along the flanks of a double plunging asymmetrical anticline extending NW – SE. The strata dip (30 – 72)º NE. Resources were estimated by 4.2 m.t. (Al-Ka'aby and Touni, 1979).

─ **Al-Jabal and Al-Heshaimia:** Wasit Governorate near Zurbatia, extension of Himreen Range, near the Iraqi – Iranian borders. Several gypsum beds interbedded with marl and claystone. The strata dip towards SW and are about 5 m thick (Shadher *et al.*, 2009).

Table 3: Gypsum occurrences recorded in the Low Folded Zone

Map *	Formation	Locality	Grade
J-37X-SE	Fatha	Zarwan-Sinjar	46.5% SO_3
J-38S-NW	Fatha	Jebel Ishkaft	46.0% SO_3
	Fatha	Safaiya	46.0% SO_3
J-38S-NE	Fatha	Gusair	45.1% SO_3
	Fatha	Ain Zala	45.6% SO_3
	Fatha	Ravan	45.8% SO_3
	Fatha	Butmah	44.9% SO_3
	Fatha	Jebel Bab Neat	46.0% SO_3
	Fatha	Masra	46.6% SO_3
	Fatha	Basitki	44.4% SO_3
J-38S-SW	Fatha	Jebel Gaulat	46.0% SO_3
	Fatha	Sinu	46.6% SO_3
	Fatha	Tel Matair	46.3% SO_3
	Fatha	Afgani	47.3% SO_3
	Fatha	Sasan	46.3% SO_3
J-38S-SE	Fatha	Jebel Shaikh Ibrahim	46.0% SO_3
	Fatha	Zainiyat	47.7% SO_3
	Fatha	Mustantiga	50.3% SO_3
	Fatha	Adayah	41.2% SO_3
	Fatha	Khawain	42.3% SO_3
J-38T-SW	Fatha	Nuwaigeet	46.5% SO_3
	Fatha	Lazzaga	46.0% SO_3
	Fatha	Hamam Al-Alil	44.0% SO_3
	Fatha	Mishraq	48.7% SO_3
	Fatha	Guwair	46.3% SO_3
I-38B-NW	Fatha	Kassab	46.3% SO_3
	Fatha	Qaiyarah	45.8% SO_3
	Fatha	Najmah	45.6% SO_3
	Fatha	Sadid	45.9% SO_3
I-38B-NE	Fatha	Qara Chouq	45.3% SO_3
I-38B-SW	Fatha	Shura	46.0% SO_3
	Fatha	Msahak	45.2% SO_3
	Fatha	Balaleej	46.6% SO_3
	Fatha	Mushayit	46.7% SO_3
I-38C-NW	Fatha	Baba Dom	49.0% SO_3
I-38I-NW	Fatha	Al-Fadhul	53.9% SO_3
I-38I-NE	Fatha	Sulaiman Beg	46.3% SO_3
	Fatha	Tuz Khurmatu	46.7% SO_3
	Fatha	Kifri	45.8% SO_3
I-38J-NW	Fatha	Bawagaru	46.0% SO_3

*Quadrangle at scale of 1: 100 000 (see Fig.1).

(After: Ma'ala, 1977; Taufiq and Domas, 1977; Al-Din *et al.*, 1977; Al-Mubarek and Youkhanna, 1976 and Mansour and Toma, 1983).

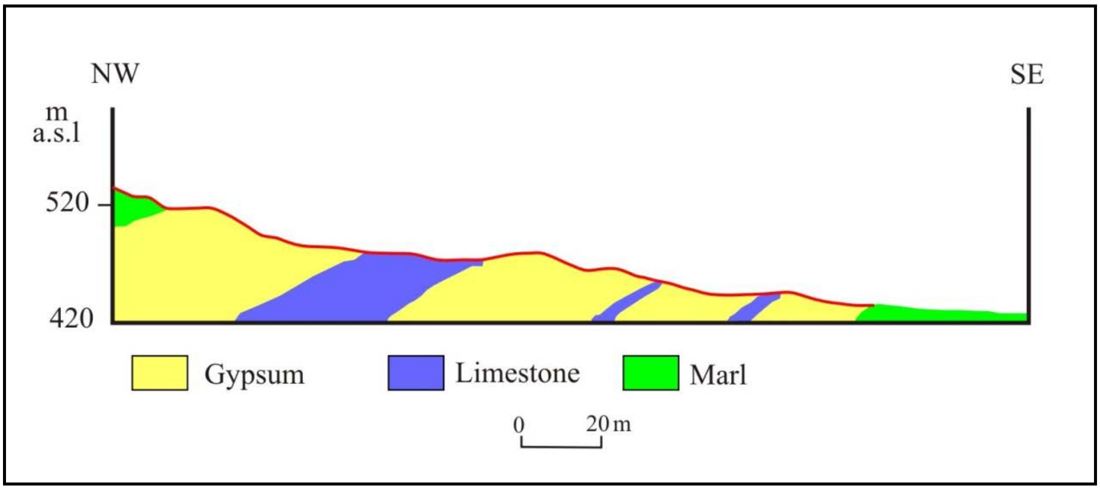

Fig.6: Geological cross section in Qara Walli gypsum deposit
(from Al-Ka'aby and Mohammad, 1976)

▪ **Rock Salt and Inland Salterns**

Rock salt deposits in Iraq are found in three main age groups: Triassic, Jurassic and Miocene. The best development of rock salt with regard to quality and thickness is in the Miocene Dhiban and Fatha formations of the Low Folded Zone (Fig.7). The Miocene rock salt deposits were developed in two main basins in the Low Folded Zone; Sinjar and Himreen. The feasibility of exploitation of these deposits is connected with several aspects which are not studied in detail yet.

– **Dhiban Rock Salt Deposits:** The thickness of the Dhiban evaporitic sequence is highly variable, depending on the location within the basin. It is generally composed of thick gypsum beds interbedded with marl and thin layers of limestone (Etabi, 1978 and Dimitrov *et al*., 1984).

In the Sinjar area (Tal Hajar No.1), near the center of the basin, the Dhiban Formation contains up to 240 m thick beds of rock salt. In the Himreen basin (Abtakh No.1) the rock salt beds range from (15 – 70) m in thickness. Potassium, as polyhalite, is present up to 2% in the Dhiban rock salt deposits.

– **Fatha Rock Salt Deposits:** The Fatha Formation follows almost the same Paleogeographic pattern as the Dhiban Formation in these two evaporitic basins. The Fatha Formation is composed in subsurface of alternations of limestone, claystone, gypsum and rock salt. The best development of rock salt in the Fatha Formation was detected in three areas: south of Sinjar, south of Kirkuk and along the Iraqi – Iranian borders, between Kut and Amara. However, rock salt was encountered in most exploratory oil wells in the Low Folded Zone including: Khabbaz, Bai Hassan (area-1 and area-2) Qara Chouq, Avanah Dome, Cham Chamal, Amshe Saddle, Baba Dome (area-1), Kor Mor II, Jambur, Himreen-1, Naft Khaneh, Jaria Pika, and Gillabat (Table 4). The few samples analyzed of the Fatha Formation rock salt show high purity with (97 – 98) % NaCl. The best development of rock salt was noticed in the middle and lower parts of the formation (Dimitrov *et al*., 1984 and Mustafa *et al*., 1984).

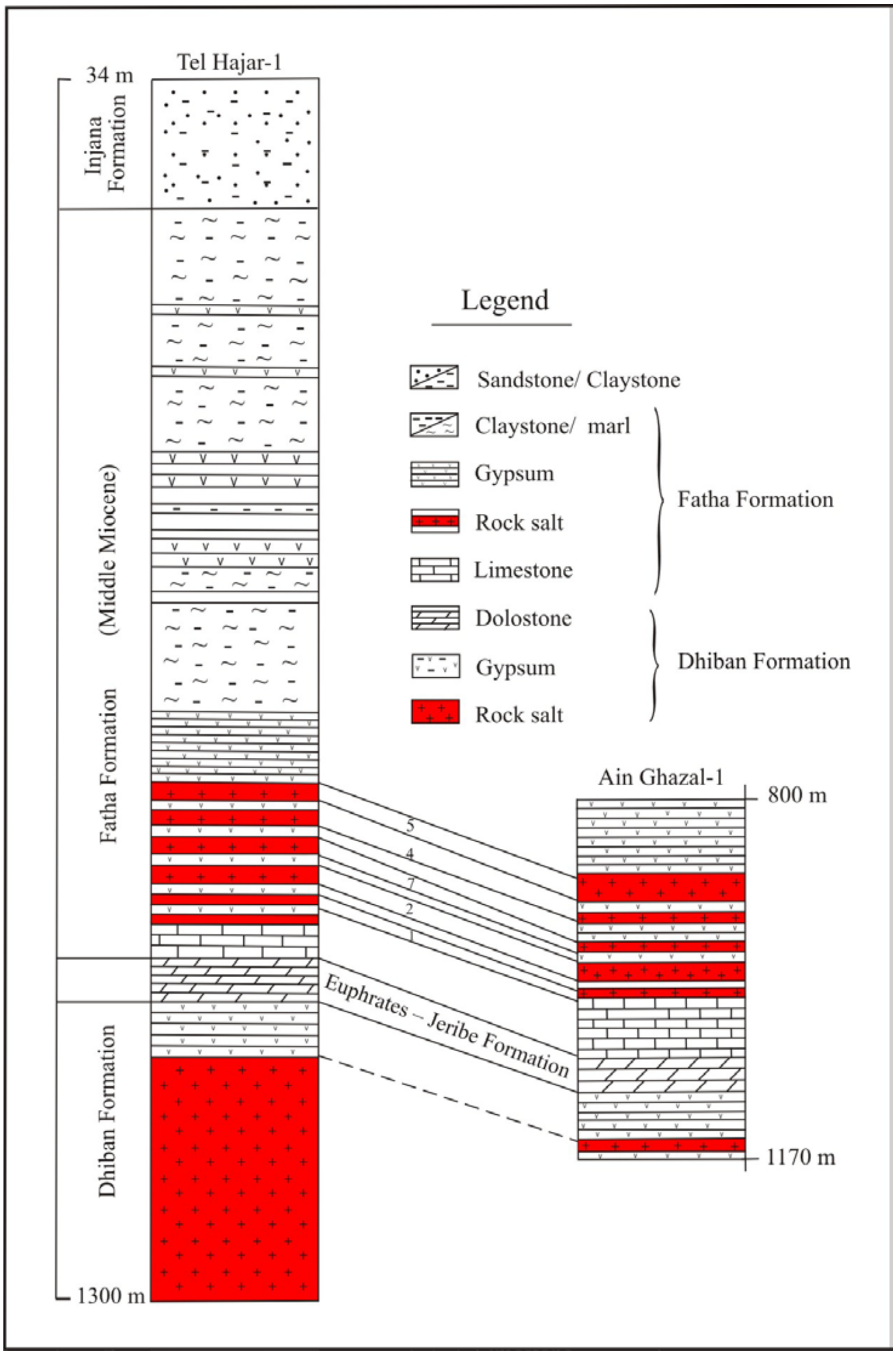

Fig.7: Columnar section in Tel Hajar and Ain Ghazal rock salt deposits (from Mustafa *et al*., 1984)

─ **Quaternary Inland Salterns:** A few salterns are located in the Low Folded Zone. These are continental salt pan deposits, usually fed by saline groundwater. The most important of which is Hawija with 97.7% NaCl, located 20 Km SW of Hawija town, and associated with bituminous seepages with NaCl-type groundwater. The salt contains about 0.5% KCl and 0.7% $CaSO_4$ (Mustafa *et al*., 1984). Other salterns, but less important, are found in Tuz Khurmatu, Khaleefa and Zurbatia.

Table 4: Rock salt occurrences in anticlinal structures of the Low Folded Zone (Etabi, 1978 and Mustafa *et al*., 1984)

Map *	Formation	Locality and well No.	NaCl
J-38S-SW	Fatha	Ain Gazal	97%
J-37X-SE	Fatha	Tel Hajar	98%
I-38B-SE	Fatha	Khabbaz	n.a.
	Fatha	Bai Hassan (area I)	n.a.
I-38B-NE	Fatha	Qara Chouq	n.a.
	Fatha	Avanah Dom	n.a.
I-38C-NE	Fatha	Cham Chamal	n.a.
I-38C-NW	Fatha	Bai Hassan (area II)	n.a.
	Fatha	Amshe Sadle	n.a.
	Fatha	Baba Dome (area I)	n.a.
	Fatha	Baba Dome (area II)	95%
I-38C-SE	Fatha	Kor Mor II	n.a.
I-38C-SW	Fatha	Jambur	n.a.
I-38I-NW	Dhiban	Himreen I	n.a.
	Fatha	Judaida	n.a.
I-38I-NE	Fatha	Pulkhana	n.a.
	Fatha	Injana	n.a.
I-38J-SW	Fatha	Naft Khaneh	n.a.
I-38J-NE	Fatha	Jaria Pika	n.a.
I-38J-NW	Fatha	Gillabat	n.a.

*Quadrangle at scale of 1: 100 000 (see Fig.1).

- **Limestone**

Iraq is very rich in industrial carbonate rocks and especially with limestone of high purity, suitable for cement and other industrial uses. The Serikagni, Euphrates and Fatha Formations (Miocene) are important limestone-bearing units in the folded zones, but thickness and quality are variable.

In the Low Folded Zone, the Fatha Formation is the main limestone-bearing rock unit with specifications suitable for cement industry. However, a few deposits and occurrences in Sinjar and Qara Chouq structures are found in Sinjar, Avanah, Serikagni, and Bajwan formations (Mansour and Petranek, 1980).

There are about 30 limestone deposits that were investigated in Iraq, a few of which are in the Low Folded Zone (Table 5). In addition, more than 20 limestone occurrences of suitable industrial composition have been outlined and analyzed during the geological survey of the area (Table 6).

Table 5: Chemical analysis of limestone deposits studied in the Low Folded Zone (wt.%)

Deposit	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
Sinjar	10.75	1.38	1.11	46.2	1.06	0.73
Badush	n.a.	n.a.	n.a.	44.1	1.57	0.50
Dimarchi	n.a.	n.a.	n.a.	41.1	1.8	0.50
Hamam Al-Alil	9.81	1.37	1.65	47.6	1.6	0.63
Qara Chouq	1.40	0.22	0.22	53.4	0.90	0.58
Zurbatia	7.28	1.85	0.80	47.83	1.12	0.34

n.a.: not analyzed

Table 6: Limestone occurrences recorded in the Low Folded Zone

Map *	Formation	Locality	Grade (Cao%)
J-37X-SE	Sinjar	Sinjar	46.2 – 54.2
	Avanah	Sinjar	53.3
	Serikagni	Sinjar	47.0 – 55.1
J-38S-NW	Euphrates and Fatha	Mushura Dagh	35.3 – 54.4
J-38S-NE	Fatha	Ain Zala	46.2 – 53.7%
J-38S-SW	Fatha	Jabal Ishkaft	44.1 – 54.6
	Euphrates and Fatha	Gusair	36.8 – 53.7
	Fatha	Gaulat	50.4 – 53.9
J-38S-SE	Fatha	Jabal Adayah	44.8 – 54.7
	Fatha	Jabal Alan	49.1 – 54.0
J-38T-SW	Fatha	Jabal Nowaigit	48.2 – 54.9
I-38B-NW	Fatha	Mishraq-Shura	55.0
I-38B-NE	Anah	Kandinawa	53.4
	Euphrates	Gomasheen	30.8 – 55.3
	Fatha	Makhmour	28.3 – 54.8
I-38C-NW	Fatha	Saralu	53.8 – 54.7
	Fatha	Kani Domilan	46.2 – 48.0
I-38C-SW	Fatha	Tarjil	43.1
I-38I-NE	Fatha	Sulaiman Beg	47.0 – 54.8

*Quadrangle at a scale of 1: 100 000 (see Fig.1).
Data were collected from: Al-Mubarak and Youkhanna (1976), Taufiq and Domas (1977), Mansour (1976), Al-Din *et al*., (1977), and Mansour and Petranek, 1980).

― **Sinjar Limestone Deposit:** Located at the eastern side of the Sinjar Mountain at Wadi Khan, about 40 Km W of Tel Afar, within the Serikagni Formation (Early Miocene). The limestone is fine grained, tough and slightly fossiliferous and alternating with marl. The reserves were estimated by about 155 m.t. (Ameen, 1980).

― **Badush Limestone Deposit:** A small deposit, mostly exploited for cement production, located about 25 Km NW of Mosul city, within the Fatha Formation. It consists of (7 – 22) m thick limestone beds at the core of Jabal Alan where the strata dip (10 – 25)º. The limestone is locally chalky, fossiliferous with occasional intercalations of green marl. The reserves were estimated by 24 m.t. on category C1 (Al-Mubarak, 1980).

― **Dimarchi Limestone Deposit:** A small deposit, mostly consumed for cement industry, located about 10 Km NW of Mosul city, within the Fatha Formation (Lower Member). The limestone is occasionally fossiliferous and travertine-like. The thickness varies from (6 – 20) m and the dip is (1 – 7)º SE. The reserves were estimated by 28 m.t. (Al-Murib, 1978) (Fig.8).

― **Hamam Al-Alil Limestone Deposit:** A small deposit, mostly consumed now by cement industry. It is one of the oldest limestone deposits investigated in Iraq, located about 22 Km S of Mosul city within the Fatha Formation. The limestone strata is about 8 m thick and horizontal (Leitch, 1954 and Toma, 1987).

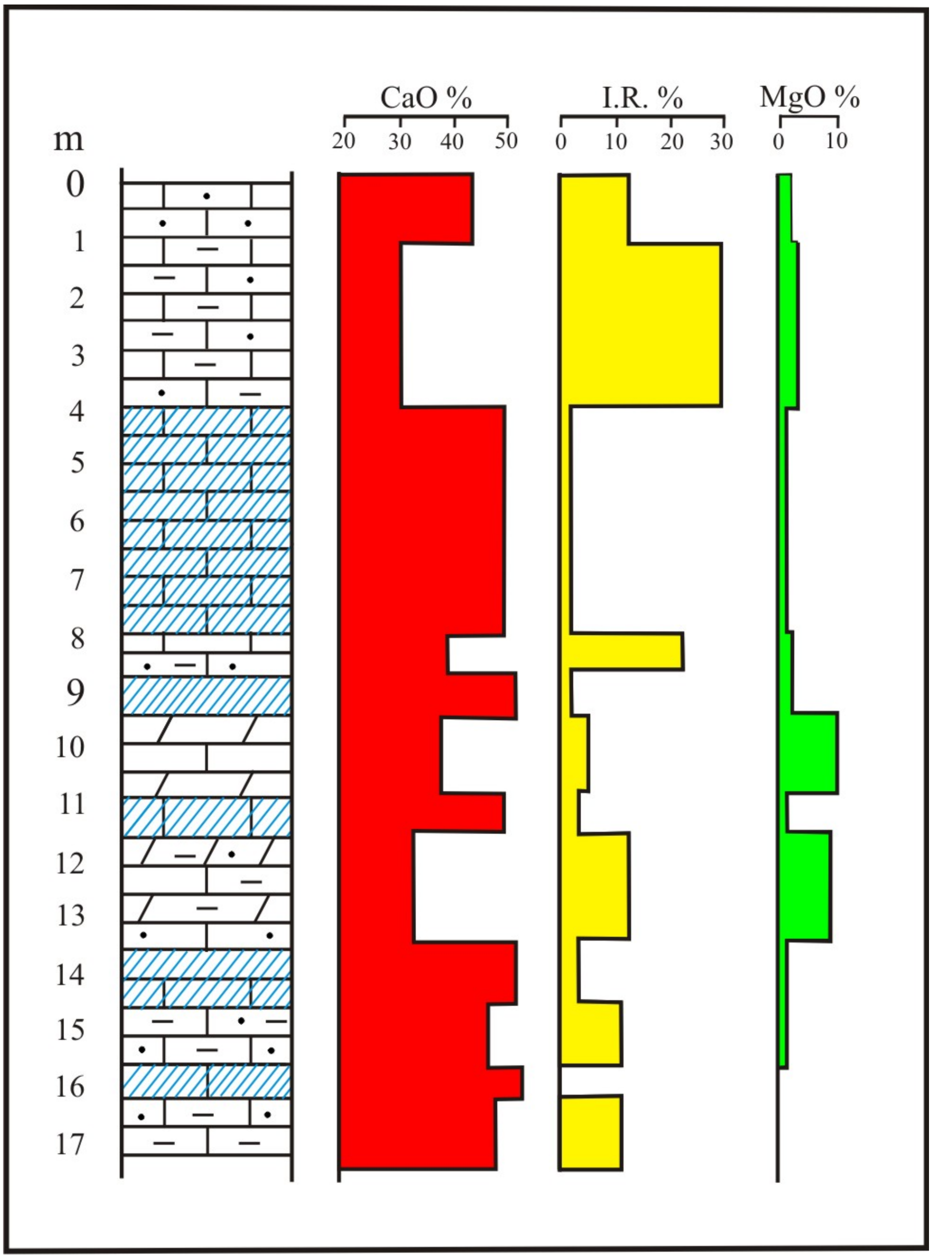

Fig.8: Geological columnar section and chemical analysis
of the Dimarchi limestone deposit
(from Al-Murib, 1978)

─ **Qara Chouq Limestone Deposit:** Located about 65 Km SW of Erbil city within Bajwan Formation (Oligocene). The limestone strata are (10 – 25) m thick, dipping (5 – 25)º NE within the southern dome of Qara Chouq Anticline (NE limb). The reserves were estimated by 30 m.t. (Al-Rufaie and Muhamad, 1976 and Al-Murib, 1980).

─ **Zurbatia Limestone Deposit:** Located about 18 Km NW of Zurbatia town within the SW flank of the southern extensions of Himreen Range. The limestone is part of the Fatha Formation; the exposed thickness is (4 – 26) m (mean 15.7 m). The reserves were estimated by 33.5 m.t. (Khalaif and Shadhur, 2009).

▪ **Dolostone**

In addition to limestone deposits and occurrences, numerous dolostone occurrences were documented during the regional geological mapping of the Low Folded Zone (Table 7). The main dolostone-bearing formations are: Avanah, Baba, Anah, Bajwan, Shurau (Oligocene), Euphrates/ Jeribe (Early/ Middle Miocene) and Fatha (Middle Miocene). They are mostly used as building stones, but some of them may be important source for magnesia in Iraq.

Table 7: Dolostone occurrences reported in the Low Folded Zone

Map *	Formation	Locality	Grade (MgO%)
J-38S-NW	Avanah	Mushura Dagh	16.6
	Jeribe	Jabal Alan	19.9
J-38S-NE	Fatha	Foidah	18.7
J-38S-SW	Fatha	Jabal Sinjar	17.0
J-38S-SE	Jeribe	Jabal Gaulat	18.6
	Avanah	Al-Mahalabiyah	18.9
	Jeribe	Al-Gnaisia	17.2
	Avanah	Jabal Atshan	18.0
	Jeribe	Jabal Nuwaigeet	18.9
	Fatha	Eski Mosul	16.7
H-38T-NW	Pila Spi	Jabal Dohuk	19.0
	Euphrates	Jabal Duhqan	20.6
J-38T-NE	Aqra – Bekhme	Aqra Dagh	18.2
	Aqra – Bekhme	Aqra	17.4
J-38T-SW	Pila Spi	Ain Al-Safra	19.2
	Pila Spi	Jabal Bashiqah	19.5
I-38B-NE	Baba	Shaikh Alas	15.7
	Fatha	Makhmour	15.8
	Euphrates	Qara Chouq	19.2
	Anah	Kurd Karawi	16.0
	Bajwan	Goma Shin	17.7
	Shurau	Qara Chouq	18.2

*Quadrangle at a scale of 1: 100 000 (see Fig.1).

Data were collected from Trashiliev (1980); Al-Sammarai and Al-Mubarak (1978); Taufiq and Domas (1977) and Al-Din *et al*. (1977).

▪ **Gravel and Sand Aggregates**

These raw materials are found in Quaternary (Pleistocene) sediments as River Terrace and Alluvial Fan Deposits and also in older formations of Mukdadiya (Late Miocene – Pliocene) and Bai Hassan (Pliocene – Pleistocene). Generally, there is more gravel than sand in these aggregate deposits. Several deposits and occurrences have been explored and documented by GEOSURV (Table 8).

— **Al-Tib:** Alluvial Fan Deposits, Quaternary, 2.9 m thick, 69% gravel, 30% sand. Located 75 Km NE of Amara city (Al-Ka'aby and Al-Bayati, 1975).

— **Chlat:** Bai Hassan Formation (Pliocene – Pleistocene), (2 – 11) m thick, 62% gravel, 38% sand. Located 30 Km E of Ali Al-Gharbi (Younan and Saib, 1976).

— **Daqooq Soo and Khassa Soo:** Valley-Fill deposits, located near Kirkuk with (70 – 80) % gravel and the rest is sand (Al-Hussain *et al*., 1976).

Table 8: Gravel – sand deposits and occurrences recorded in the Low Folded Zone

Map *	Formation	Locality	Gravel/sand (%)
J-38T-SE	River Terraces (Q)	Zankal	75/24
	River Terraces (Q)	Safia	72/26
	River Terraces (Q)	Kanhash	68/30
	River Terraces (Q)	Aski Kelek	70/29
	River Terraces (Q)	Tel Allaban	58/41
	River Terraces (Q)	Al-Mankouba	65/35
	River Terraces (Q)	Saif Dinan	63/37
J-38T-NW	River Terraces (Q)	Hamam Al-Alil	70/29
	River Terraces (Q)	Dair Mekhail	79/20
	River Terraces (Q)	Hawi Al-Kanisa	55/45
	River Terraces (Q)	Rashidia	78/21
	Mukdadiya	Ain Al-Safra	n.a
J-38S-SE	River Terraces (Q)	Badush	75/25
	River Terraces (Q)	Aski Mosul	78/21
	River Terraces (Q)	Shorekan	69/31
J-38S-NE	River Terraces (Q)	Jenken	61/36
	River Terraces (Q)	Shaikh Humci	74/25
	River Terraces (Q)	Tel Abu Dahir	68/31
	River Terraces (Q)	Khanek	70/29
	River Terraces (Q)	Upper Kamouna	71/28
	Injana	Dohuk – Ain Zala	Sand/ n.a.
I-38B-SW	Injana	Igmisa	Sand / n.a.
I-38B-NW	Aeolian Deposits (Q)	Fatha	Sand/ n.a.
J-38U-SW	Mukdadiya	Qara Chouq	n.a.
	Bai Hassan	Taq Taq	n.a.
	Injana	Shaqlawa	n.a.
I-38I-NE	River Terraces (Q)	Aq Su	75/23
	Injana	Pulkhana	Sand/ n.a.
I-38X-SW	Aeolian Deposits (Q)	Chlat – Teeb	100% sand
	Bai Hassan	Al-Tib (small deposit)	69/30
	Aeolian Deposits (Q)	Abu Grab	100% sand
I-38W-NW	Fan Deposits & River Terraces (Q)	Chlat (large deposit)	62/38
I-38P-SE	Fan Deposits & River Terraces (Q)	Wadi Thera'a (small deposit)	58/41
I-38P-NE	Fan Deposits & River Terraces (Q)	Galal Haran (small deposit)	78/21
	Fan Deposits & River Terraces (Q)	Galal Tehlaw (small deposit)	73/26
	Fan Deposits & River Terraces (Q)	Galal Tersak (small deposit)	81/18
I-38J-SW	River Terraces (Q)	Tobzan (small deposit)	74/25
	River Terraces (Q)	Madan (small deposit)	70/29
	River Terraces (Q)	Jalawla'a (small deposit)	70/29
I-38J-NE	River Terraces (Q)	Diyala (small deposit)	63/35
I-38J-NW	River Terraces (Q)	Wadi Kabejkena (small deposit)	75/24
	River Terraces (Q)	Wadi Isai	75/24
	Bai Hassan	Kifri	(G/S) n.a.
	Bai Hassan	Kalar	(G/S) n.a.
I-38I-SE	Bai Hassan	Tuz Khurmatu	(G/S) n.a.
	Mukdadiya	Hasan Al-Behaibi	(G/S) n.a.

*Quadrangle at scale of 1: 100 000 (see Fig.1).
n.a.: not analyzed, Q: Quaternary
Data From: Hagopian and Vejlupek (1977); Al-Sammarai and Al-Mubarek (1978); Sissakian (1979) and Barwari (1979).

─ **Jalawla'a:** River Terraces along Diyala River, with 70% gravel (Younan, 1980b).

─ **Mandali:** Several deposits of river terraces are found in Galal Haran, Galal Tehlaw, Galal Tersak and Wadi Thera'a. Gravel content varies from (57 – 81) % and the rest is sand. The sulfate content is less than 0.3% SO_3 (Al-Hussain and Saib, 1981).

─ **Mosul:** Several small deposits of gravel/ sand were investigated in the Mosul area in River Terraces. These are renewable resources (Al-Ka'aby, 1975).

─ **Greater Zab:** A number of gravel-sand deposits were investigated in the Quaternary River Terraces of the Greater Zab River, such as Zankal, Safia, Aski Kalek and Kanhesh. They consist of (65 – 75) % gravel and are (1.5 – 2.0) m thick (Al-Ka'aby *et al*., 1976).

▪ **Bentonite**

Bentonite deposits were discovered in the Himreen South range in the early seventies. Two deposits were investigated within the Mukdadiya Formation (Late Miocene – Pliocene). These are Zarlukh and Qara Tappa. Both sites show some old workings of excavations. The bentonite is found as lenticular bodies in association with tuffa, sandstone and siltstone.

─ **Zarloukh Deposit:** Situated 18 Km W of Qara Tappa town. The investigated area is about 0.3 Km^2 extending about 1400 m along the strike (SE – NW). The wall rocks are composed of cross-bedded sandstones of the Mukdadiya Formation. The bentonite "bed" is composed of gray or brown montmorillonite-rich horizon, (0.5 – 1.8) m thick, overlain by 2.7 m thick gray or white sandy-clayey horizon, with montmorillonite admixture. The overlying bed consists of (1 – 3) m thick dark gray sandstone. The montmorillonite is Ca-based, and vary in the deposit from (3 – 93) %. The chemical composition is shown in Table (9) and the reserves were estimated by about 0.3 m.t. (Zainal and Jargees, 1973).

─ **Qara Tappa Deposit:** Situated about 17 Km SW of Qara Tappa town within the Himreen South range. The deposit is part of the Mukdadiya Formation. The deposit, as described by Zainal and Jarjees (1972) consists from bottom to top as basal green sandstone, overlain by thin bed of marl, followed by gray medium grained sandstone. The main bentonite horizon occurs within the overlying (6 – 9) m thick marl bed, and consists of up to 2 m thick (average about 1 m), irregular and lenticular in form; overlain by white and light gray tuffaceous horizon.

The mineral analysis showed up to 80% Ca-montmorillonite with impurities of illite, chlorite and quartz. The chemical composition is shown in Table (9). The reserves were estimated by about 0.4 m.t. on all categories (Zainal and Jargees, 1972).

─ **Emgarin – Tayawi Deposit:** Located within the NE limb of the Himreen range, about 140 Km NE of Baghdad, along Kirkuk – Baghdad highway. The deposit is 1.5 Km^2 in area and includes two neighboring locations: Abu Gharib and Ausija. All of which are within the Mukdadiya Formation. The bentonite-bearing sequence consists of basal sandstone, dark gray and cross bedded, overlain by light brown claystone, which is topped by (0.8 – 3.2) m thick montmorillonite-rich horizon. The bentonite is brown, compact and light weight. The overlying unit consists of tuffaceous sandy material, white, current bedded and laminated, topped by siltstone, mudstone and sandstone. The mineral analysis showed (8 – 63) % montmorillonite content, with impurities of illite, kaolinite and quartz. The chemical composition is shown in Table (9). The reserves were estimated by 0.37 m.t. (Al-Maini, 1975).

Table 9: Chemical analysis of the Himreen bentonites (wt.%)

Oxides	Zarloukh *	Qara Tappa *	Emgarin – Tayawi **
SiO_2	57.79	57.47	57.30
Al_2O_3	16.53	19.63	16.00
Fe_2O_3	3.20	3.58	3.30
CaO	4.40	4.25	4.70
MgO	7.00	5.07	6.15
K_2O	0.12	n.a.	0.70
Na_2O	0.17	0.21	1.00
H_2O^+	10.30	10.51	9.50

* Zainal and Jargees (1972), ** Al-Maini (1975)

- **Palygorskite**

Interesting palygorskite occurrences have been discovered and studied in Ba'ashiqa and Jabal Maqloub near Mandan Village NE of Mosul city. The pioneer studies were made by Al-Sayegh *et al*. (1976) and Al-Banna (1977). The palygorskite showings were found to occur as fillings along shear fractures, joints and fault planes. It occurs as creamy white fillings in the clastics of Injana Formation (Late Miocene). Locally, the palygorskite fillings may reach (2 – 3) cm in thickness and extend for several meters or tens of meters along fracture and fault planes.

Under the microscope, the mineral is fibrous in habit with straight extinction, sometimes wavy. The fibers are randomly oriented (Fig.9). The mineral samples were examined by X-ray diffraction, DTA and IR techniques, which showed typical patterns of palygorskite (Al-Sayegh *et al*., 1976) (Fig.10).

The origin, discussed by previous authors was not conclusive, although Al-Sayegh *et al*. (1976), proposed a hydrothermal origin as an early impression. In the genetic classification proposed by Al-Bassam *et al*. (2000) for Iraqi palygorskites, it was considered a group in itself as "Direct chemical precipitation from solution". The age of the mineralization is obviously Pliocene or post Pliocene and the fillings must have taken place directly after the fractures, veins and fault planes were opened in view of the pure nature of the palygorskite fillings. Some chemical analysis are presented in Table (10) after Al-Sayegh *et al*. (1976) and Al-Banna (1977).

Table 10: Chemical analysis of some palygorskite samples from Ba'shiqa and Jabal Maqloub areas (wt.%)

SiO_2	58.80	60.10	61.32	62.01
Al_2O_3	11.89	10.33	11.58	11.61
Fe_2O_3	0.71	0.75	0.85	0.88
CaO	0.42	0.30	0.20	0.51
MgO	10.40	9.50	11.10	9.12
K_2O	0.12	0.12	0.22	0.21
Na_2O	0.03	0.10	0.20	0.20
L.O.I.	14.97	17.34	15.21	16.09

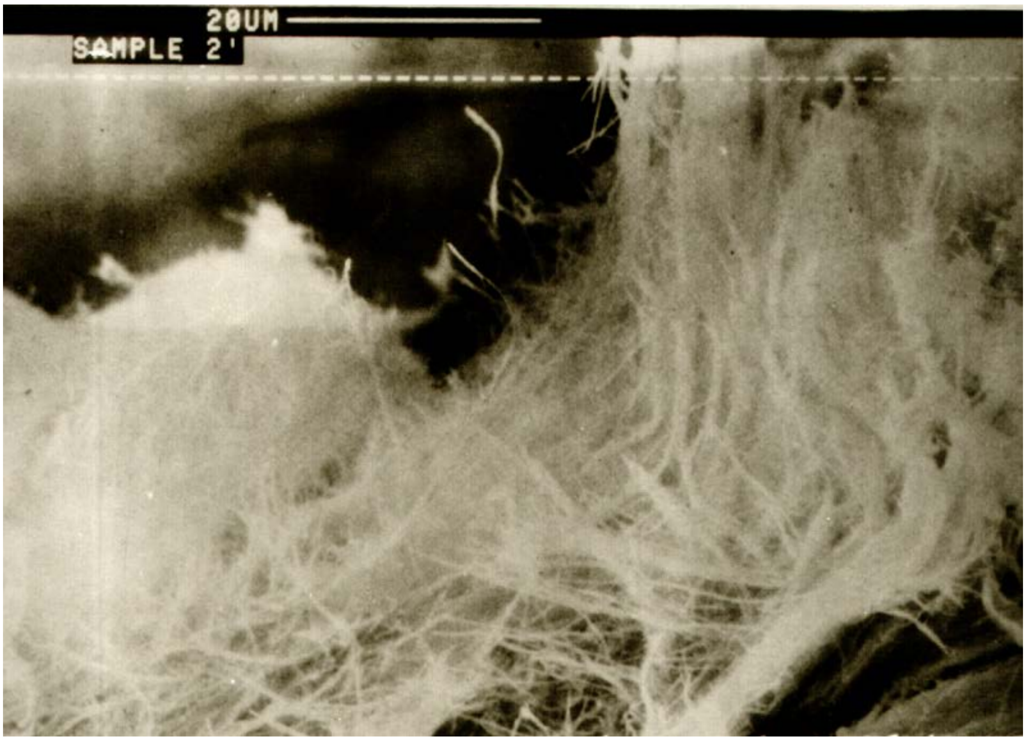

Fig.9: Well developed palygorskite fibres of Jabal Maqloub deposits (SEM)
(Al-Bassam *et al*., 2000)

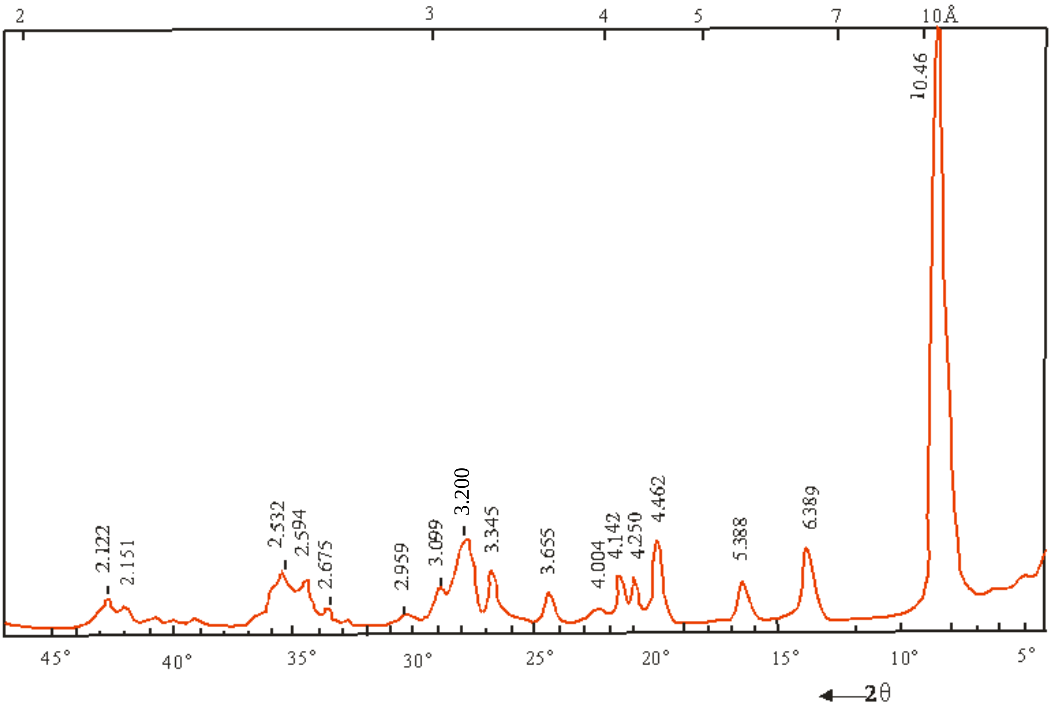

Fig.10: X-ray diffractograms of Jabal Maqloub palygorskite
(from Al-Sayegh *et al*., 1976)

▪ **Quaternary Mud (for cement and bricks industries)**

These are available in the flood plain deposits and synclinal fill deposits of the Low Folded Zone. They meet the requirements of Portland cement production and to some extent bricks industry. However, the relatively high concentration of lime in these mud sediments highly limits meeting the required specifications for bricks making. Several deposits were investigated to meet the cement industry demands. They have been under exploitation for several years now.

– **Kasak:** Located about 10 Km from Tel Afar town. The Quaternary mud sediments are (0.5 – 13) m thick underlain by the Injana Formation. The mineralogy includes: montmorillonite, kaolinite, chlorite, calcite and quartz. The reserves were estimated by about 25 m.t. (Shabaneh, 1980 and Nadir, 1981).

– **Tel Al-Banat:** Located about 15 Km south of Mosul – Sinjar Highway. The Quaternary mud deposits are (2.8 – 3.7) m thick and consists of clay, silt and sand of various mineral composition. The chemical analysis is shown in Table (11). The reserves were estimated by 3.0 m.t. on category C1 and 17.5 m.t. on category C2 (Jabbouri, 1984).

Table 11: Chemical composition (wt.%) of Quaternary mud for cement and bricks and physical tests of bricks

Oxides	**Kasak**	**Tel Al-Banat**	**Lailan**	**Kirkuk**
SiO_2	35.2	11.8 – 36.2	38.5	36.8
Al_2O_3	9.50	1.4 – 9.2	9.50	8.4
Fe_2O_3	5.20	1.04 – 8.9	4.65	4.2
CaO	22.3	21.3 – 45.2	19.4	20.3
MgO	3.9	0.7 – 4.2	4.3	3.9
K_2O	1.4	0.15 – 2.72	1.3	0.02
Na_2O	0.7	0.0 – 0.7	1.2	0.08
SO_3	0.07	0.07 – 5.8	0.87	2.3
L.O.I.	21.6	n.a.	19.2	17.0

Tests	**Specifications***	**Results**
Compressive Strength (MPa)	270 min	172 – 359
Linear Shrinkage (%)	5 max	0.0 – 2.1
Volume Shrinkage (%)	5 max	0.3 – 8.0
Water absorption (%)	20 max	18 – 24
Firing temperature (ºC)	950 – 1050	950

*Iraqi standards

– **Lailan:** Located 12 Km, south of Kirkuk city. The Quaternary mud sediments are silty clay, loam and sandy clay with sulfate and carbonate rock fragments. The sediments are about 11 m thick and the chemical composition is given in Table (11). The reserves were estimated by about 20 m.t. (Toma and Butris, 1978).

A few mud sediments were investigated for bricks industry in the Low Folded Zone. The main obstacle is the high lime content of these sediments, induced by carbonate rock fragments commonly present as admixture.

─ **Kirkuk:** Located 15 Km from Kirkuk city. The sediments are 6 m thick and the reserves were estimated by 8.3 m.t. (Shafiq, 1981). Analysis and test results are given in Table (11).

─ **Mudrocks in Older Formations:** A great potential exists in the mudrocks of the Fatha and Injana formations exposed in the Low Folded Zone. However, these mudrocks, though suitable for cement industry, they sometimes need some makeup to render them suitable for bricks industry. The problem is usually the excess lime in these mudrocks, which can be dealt with via mixing with high silica sand or silt.

▪ **Iron**

Concretions of Fe-oxyhydroxides and goethite cubes (after pyrite) were reported in the marls of the Sinjar Formation () at Jabal Sinjar structure (Ma'ala, 2001). Red Stains are common and have lenticular shape. The Fe_2O_3 content in red, oxidized and weathered marls ranged from (0.3 – 9.9) %. Iron oxyhydroxides coat calcite crystals or found disseminated. Traces of hematite and jarosite were also identified in these ferruginous rocks.

Using remote sensing techniques and field checking, Ahmed (2009) found that the iron oxyhydroxide showings are present in terrains covered by several formations exposed in the Sinjar anticlinal structure; including Shiranish (Late Cretaceous) (16.7% Fe_2O_3), Sinjar (Middle Paleocene – Early Eocene) (2.2 – 9.4% Fe_2O_3), Injana (Late Miocene) (5.4 – 7.4% Fe_2O_3) and Quaternary slope sediments (3.5% Fe_2O_3) (Fig.11).

Fig.11: Iron oxyhydroxide exposures within the Injana Formation in Jabal Sinjar area (from Ahmed, 2009)

▪ **Phosphate**

Phosphate fragments, associated with glauconite, mark the unconformable contact between Jaddala (Eocene) and Ibrahim (Oligocene) formations in Sinjar Anticline exposures (Fig.12). The phosphate is brown in color, present as fragments, fillings and phosphatized fossil shells. Microscopic examination and X-ray diffraction analysis (Fig.13) showed that the phosphate is composed of francolite (carbonate fluorapatite) (Al-Ani, 2005). The occurrence is of no economic potential.

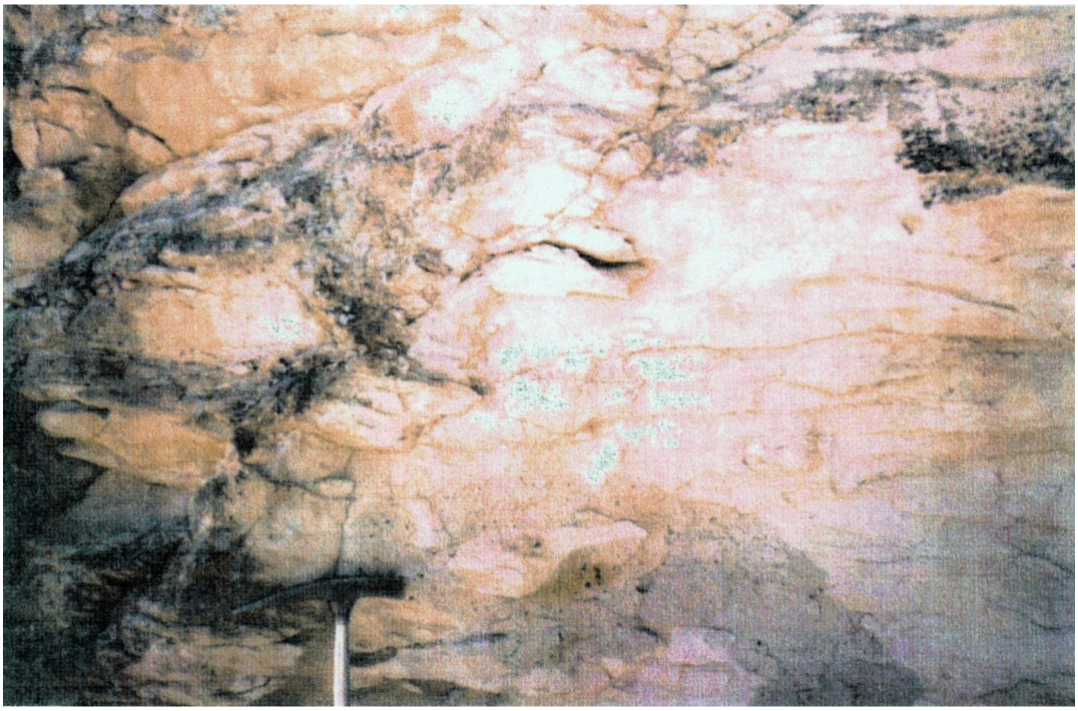

Fig.12: Phosphate showings (brown) at the upper contact of the Jaddala Formation (Al-Ani, 2005)

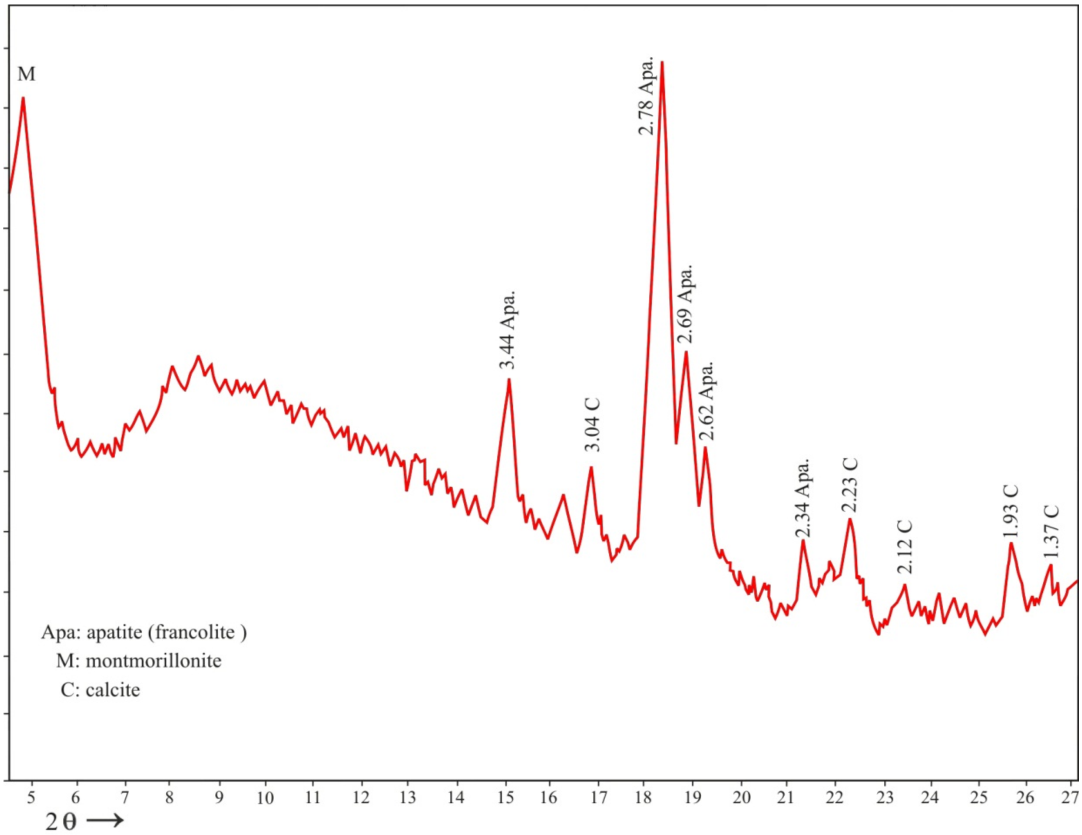

Fig.13: X-Ray diffractogram of the phosphate, showing francolite structure (Al-Ani, 2005)

DISCUSSION: MINEROGENESIS

In this respect, the reported deposits and showings of minerals and industrial rocks of the Low Folded Zone can be classified into two groups: Those related directly to the primary depositional environment, which include: Phosphate, limestone, dolostone, gypsum, rock salt (marine environments) and gravel – sand aggregates (fluvial and fluvio – marine environments). In this group paleogeographic configuration, facies and climatic conditions played the major role in minrogenesis. On the otherhand the rest of the mineral deposits and showings are related to epigenetic processes of mineral formation. They include native sulfur, bentonite, palygorskite and Fe-oxyhydroxide. They are mostly the products of epigenetic alteration or transformation processes.

The phosphate occurrences at the top of the Jaddala Formation (Early – Middle Eocene) in the Sinjar Anticline marks the unconformity with the overlying formation. It is common to find phosphate and glauconite in such surfaces and indicate slow or non-depositional environment, marked by pitted and burrowed hardgrounds (Krumbein and Sloss, 1963).

On the otherhand, the Middle Eocene in the Arabian Shelf is the last episode of phosphogenesis in the Tethyan region. More pronounced phosphate deposits were recorded in age-equivalent rock units (such as the Damluk Member of the Ratga Formation in the Western Desert) in Iraq and other parts of the region (Al-Hashimi and Al-Bassam, 2006). The phosphogenic event at the top of the Jaddala Formation may indicate open marine communication with the main Tethyan ocean at its concluding stages. The origin of these phosphates includes biological and chemical precipitation of francolite and phosphatization of carbonate shells.

Karim and Barlette (1980) confirmed the Middle Eocene age of the Jaddala Formation in Jabal Gaulat section, near Sinjar, based on index fossils. The foraminiferal assemblage they found, were considered indicative of warm (tropical – subtropical) open marine environment. They considered the presence of glauconite fragments, worm tubes (borrings) and echinode spines in the mudstone matrix at the upper part of the formation to indicate the unconformity surface with the overlying formation of Oligocene age.

The carbonates (limestone and dolostone) were deposited in various marine environments ranging from off shore open marine (Jaddala, Serikagni and Ibrahim formations), reef, back reef and fore reef (the Oligocene reef complexes), inner shelf and inter tidal flats (Euphrates and Fatha). The limestones are chemical and biochemical precipitation. Dolomitization took place in the early diagenesis (Fatha and Euphrates formations) or late diagenesis (Reefal formations) (Al-Bassam and Saeed, 1980).

The Middle Miocene represents the most important minerogenic age in the Low Folded Zone, represented by the Fatha Formation with its versatile mineral resources (Al-Bassam, 1984 and Dimitrov *et al*., 1984). The geologic history of the Low Folded Zone in the Middle Miocene was characterized by vertical block movements, which were the main factor in the cyclicity and frequent isolation of the Middle Miocene basin (Tucker and Shawket, 1980). Various types of limestones were deposited in different marine environments including agitated subtidal (grainstones), intertidal ponds and lagoonal environments (laminated non-dessicated lime mudstone) and intertidal flats (pelloidal and stromatolitic limestones). The marls and claystones are of two colors; the green and gray colors indicate quite deeper water environment, and the red color indicates shallow water to subaerial environment (Tucker and Shawket, 1980).

Gypsum was deposited in isolated basins and sabkhas by evaporation. The cyclicity with carbonates and claystones indicate frequent normal seawater fluxes. Gypsum deposits of the Fatha Formation show various structures (Tucker and Shawket, 1980), mostly nodular; nodules (2 – 10) cm with thin seams of clay, carbonate or organic matter between nodules. Bedded or layered varieties also occur, (2 – 5) cm thick, as planar, undulating and occasionally contorted, continues for several meters. The nodular and layered gypsum varieties may have precipitated in supratidal sabkha environment in association with algal mats, similar to present day deposits of the Arabian Gulf coasts (Tucker and Shawket, 1980).

Salt (NaCl) was deposited occasionally in the center of (2 – 3) basins in the Low Folded Zone (Fig.14), indicating complete basin isolation and evaporation under arid climatic conditions. Halite can be precipitated subaerially in sabkhas (Shearman, 1970), and subaqueously in shallow or deep water settings. Its restriction to basin centers of the Fatha Formation indicates basin isolation from world oceans. The occurrence of polyhalite suggests, according to Tucker and Shawket (1980), that the basin was desiccated, since the majority of potash salts form in subaerial sabkhas or playa at the end of the evaporation cycle.

A major tectonic upheaval took place in the Late Miocene – Pliocene due to collision of the Arabian Plate against Iranian and Anatolian Plates. This compressive event resulted in the folding, crumbling and deformation of the older sedimentary strata in the folded zones of Iraq.

Orogenic uplift of the Zagros Fold – Thrust Belt and subsidence of the foredeep and ahead of it resulted in the deposition of thick sequences of terrigenous clastics (molasses) in the foredeep areas in the Late Miocene, Pliocene and Pleistocene (Injana, Mukdadiya and Bai Hassan formations). Most of the Low Folded Zone was the depocenter of the Neogene molasse derived from the uplifted High Folded, Imbricate and Thrust Zones (Jassim and Buday, 2006). This pattern of clastics deposition continued through the Pleistocene as river terraces and fan deposits of considerable thicknesses.

The Late Neogene tectonic movements in the region and the structural deformation resulted, among other things, in faulting, shearing and fracturing of the sedimentary strata. The palygorskites of Jabal Maqloub and Ba'ashiqa were deposited directly from alkaline solutions, rich in Mg^{2+} and Si^{4+}, in freshly opened fractures and fault planes. Clear slicken side surfaces were noticed by the author on the palygorskite fillings, indicating that both events; fracturing and palygorskite precipitation were most probably at the same time and closely related. The mineralizing solutions were probably of normal (atmospheric) temperature and they probably ascended from deeper parts of the Injana Formation or the underlying Fatha Formation. Some of the palygorskite “veins” are deep rooted (tens of meters) (Al-Banna, 1977).

Volcanism in neighboring regions (NE of Iraq) were reported as a result of subduction of the Arabian Plate in the Late Neogene beneath Iranian Plate (Zainal, 1977). Airborne volcanic ash may travel for long distances, but finally it settles down and precipitates. Such event is recorded in several places within the fluvial clastics of the Mukdadiya Formation in Himreen Range. True “bentonite” is derived from the alteration of volcanic ash. Remnants of glass shards were identified in thin sections in the Qara Tappa bentonites (Zainal, 1977) and were taken as evidence on the origin of these bentonites, which were noticed in several other localities in the Low Folded Zone in association with tuffaceous rocks, within the Mukdadiya Formation, probably marking the same volcanic event.

The final inversion of the Sinjar Graben into an anticlinal structure (Lovelock, 1984), following the Neogene compression phase resulted in the exposure of rock units as old as Late Cretaceous (Shiranish Formation) at the core. Erosion and subaerial oxic weathering in the Pleistocene wet climate led to the oxidation of pyrite commonly present in these rock units. Pyrite nodules, concretions and cubes are frequently recorded in the Shiranish, and Sinjar formations at Jabal Sinjar and other localities (Ma'ala, 1977). These pyrite deposits are synsedimentary in origin, precipitated in an anoxic environment, and upon oxidation gave rise to local concentrations of Fe-oxyhydroxides reported in the Sinjar area.

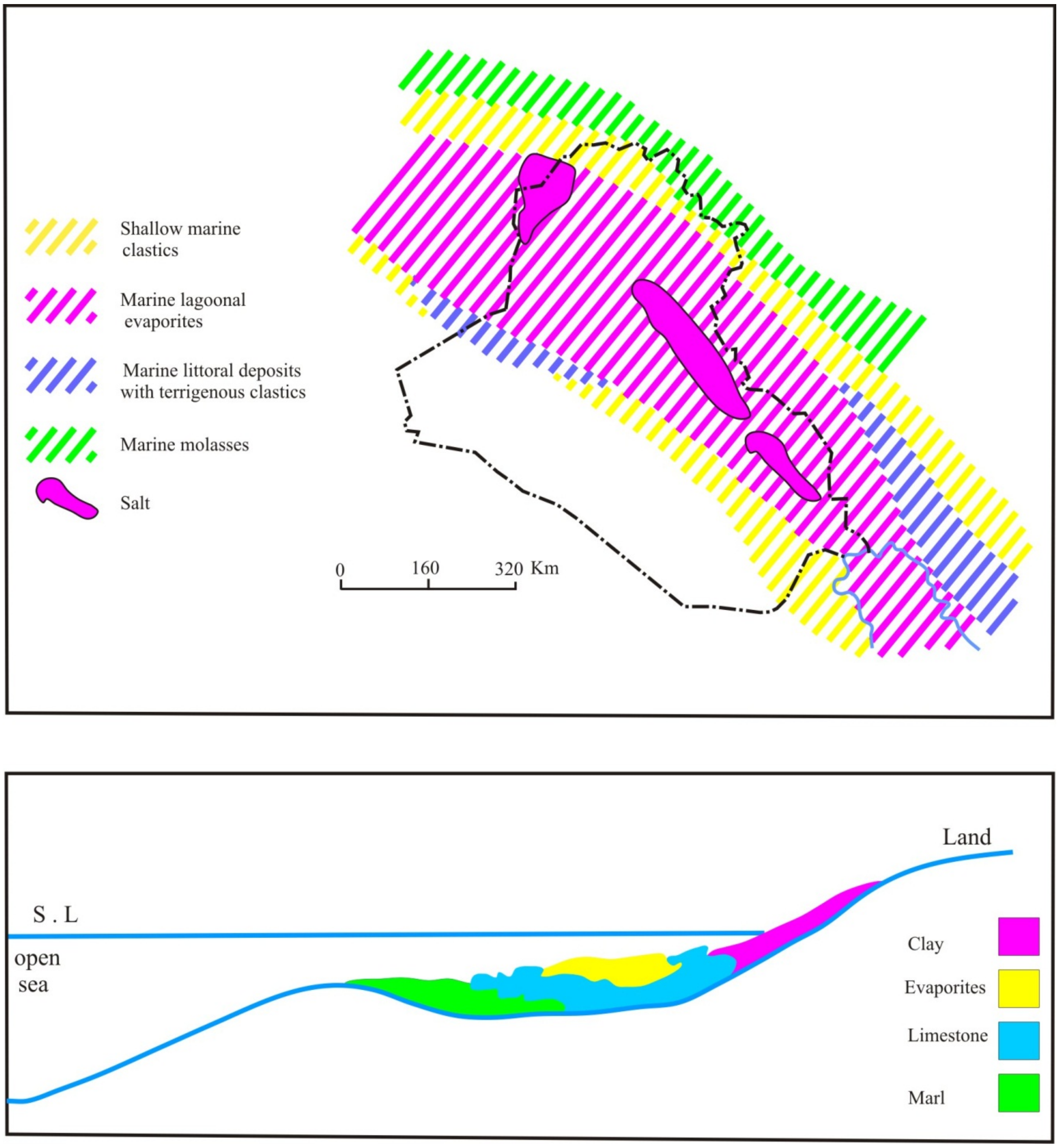

Fig.14: Middle Miocene facies distribution (Buday, 1980)

Native sulfur may form in sedimentary host rocks via various processes. In the Low Folded Zone, deposits a multiple reduction/ oxidation processes may have been the major minerogenic factor in the precipitation of native sulfur in the Fatha Formation. Gypsum was suggested as parent material according to the following sequence of chemical and biochemical reactions (Al-Sawaf, 1977):

$$CaSO_4 + CH_4 + \text{Bacteri} \xrightarrow[\text{reduction stage}]{\text{low Eh}} H_2S + CaCO_3 + H_2O + \text{Energy}$$

$$2\ H_2S + O_2 \xrightarrow[\text{oxidation stage}]{\text{high Eh}} 2\ S + 2\ H_2O + \text{Energy}$$

This model of sulfur genesis requires certain geological criteria to be available:

- Sulfate-bearing mother rocks
- Proximity to hydrocarbons
- Active hydrodynamics
- Structural trap
- Reducing conditions
- Oxidizing conditions

These geological conditions were found present in most sulfur deposits of the Low Folded Zone, which are, so far, only found in the gypsum-bearing Fatha Formation, in anticlinal structures highly fractured, with bituminous deposits and with very active hydrogeologic conditions. Moreover, Fouad (2002) noticed that most native sulfur deposits in Iraq are found in the Lower Member of the Fatha Formation in anticlinal structures located near to or cut by the Tigris River. The mineralization may have started in the Late Pliocene and/or Pleistocene and still in progress till now (Fouad *et al*., 2004).

CONCLUSIONS

- The Low Folded Zone is characterized by a number of important mineral resources. The identified resources include about one billion tons of native sulfur, 160 m.t. of primary gypsum, 270 m.t. of limestone, 48 m.t. of Quaternary mud suitable for cement industry and about 0.8 m.t. of bentonite. In addition, unlimited resources of rock salt are inferred and interesting showings of Fe-oxyhydroxides, palygorskite and phosphate were also identified.
- The genetic development of the mineral resources in the Low Folded Zone is mainly controlled by facies and lithological composition of the Neogene rock units, structural development of the area, climatic conditions and epigenetic processes.
- Two main genetic groups of mineral resources were identified: **i)** those directly related to primary depositional environment including marine deposits (phosphate, limestone, gypsum and rock salt) and fluvial and fluviomarine (gravel – sand aggregates) and **ii)** those developed as a result of epigenetic processes (bentonite, palygorskite, Fe-oxyhydroxides and native sulfur).
- The Fatha Formation (Middle Miocene) is the main rock unit in the Low Folded Zone with economic mineral deposits including: native sulfur, limestone, gypsum and rock salt.
- The identified mineral resources in the Low Folded Zone are suitable raw materials to support various types of chemical and constructions industries.

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