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THE KAOLIN CLAY DEPOSITS IN THE WESTERN DESERT OF IRAQ: AN OVEREVIEW

Mazin Y. Tamar-Agha[1], Mohammad A.A. Mahdi[2] and Asmaa A.A. Ibrahim[3]

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ABSTRACT

Very large kaolin clay deposits are recorded at the Western Desert of Iraq, in the Ga'ara Formation (Permocarboniferous), Hussainiyat Formation (Lower Jurassic), and Amij Formation (Middle Jurassic) and as flint clay at the base of the Hussainiyat Formation in karsts developed in the Ubaid Formation carbonates. Other exposed formations, such as Zor Hauran Formation (Upper Triassic) incorporate some thick impure kaolinitic horizons. The investigated clays are sedimentary (transported) except the flint clay, which is from in situ alteration of kaolin during bauxitization. The Ga'ara and Hussainiyat kaolin clays are of fluvial origin, Amij kaolin clay of paralic origin and Zor Hauran kaolinitic clay of marine origin.

Kaolinite is the major clay mineral present in these deposits with minor proportions of illite and mixed-layer illite-smectite. The other main admixtures present are quartz, iron oxyhydroxides (mostly goethite) and anatase. Particle size of these deposits ranges from very fine to coarse and their plasticity ranges from super-plastic to moderately plastic, except the Hussainiyat flint clay is non-plastic. Tests on nature of slaking showed that the Ga'ara and Amij kaolin clays disintegrate within 2 – 4 minutes after immersion in water, whereas the Hussainiyat kaolin clays require longer time to disintegrate. Thermal behavior revealed that clays with little impurities sustain higher temperatures and hence physical properties of the test tiles level off at temperatures as high as 1200 °C. On the other hand, clays containing high impurities, such as alkalies and iron oxides, level off at temperatures ranging from 1050 to 1100 °C. Thermal behavior of the silty clay differs from the rest as the linear shrinkage and bulk density show gradual and very slight increase with rise of firing temperature, whereas its open porosity and water absorption decrease in a steeper gradient.

The kaolin clays are classified, for industrial purposes, into two classes: white kaolin clays ($Al_2O_3 \geq 20\%$ and $Fe_2O_3 < 3\%$) and coloured kaolin clays ($Al_2O_3 \geq 20\%$ and $Fe_2O_3 \geq 3\%$). Follow-up investigations were carried out on eighteen localities to estimate, verify and categorize the quantity and quality of the kaolin clay deposits. The investigations at the Ga'ara locality resulted in estimating about 960 million tons of white and coloured kaolin clay (categories A, C_1 and C_2), at the Hussainiyat locality about 311 million tons of white and coloured kaolin clays (categories C_1 and C_2), at Amij locality 32 million tons of coloured kaolin clays (category C_2) and at Northeast Hussainiyat locality about 10 million tons of flint kaolin clay.

[1] Professor Emeritus, Department of Geology, College of Science, University of Baghdad, Iraq, e-mail: mtamaragha@yahoo.com
[2] Retired Expert, Iraq Geological Survey, Baghdad, Iraq.
[3] Retired Senior Geologist, Iraq Geological Survey, Baghdad, Iraq.

رواسب طين الكاؤولين في الصحراء الغربية العراقية: نظرة شاملة

مازن يوسف تمارآغا و محمد عبد الأمير مهدي و أسماء عبد العزيز ابراهيم

المستخلص

تم استكشاف كميات كبيرة جدا من رواسب طين الكاؤولين في الصحراء الغربية العراقية في تكوينات الكعرة (برموكربوني) والحسينيات (جوراسي أسفل) وعامج (جوراسي أوسط) و طين فلنتي يسفل تكوين الحسينيات موجود في خسفات متكونة في الصخور الجيرية لتكوين العبيد، فضلا عن تكشفات لتكوينات أخرى مثل تكوين زور حوران (الترياسي الأعلى) اللذي يحوي طبقات سميكة من الكاؤولين غير النقي. تدل الأطيان المستكشفة بأنها رسوبية (منقولة) ما عدا الطين الفلنتي اللذي تبين بأنه محلي النشأة تكون خلال البكستة. تبين أن أطيان تكويني الكعرة والحسينيات أصلها نهري وأطيان تكوين عامج أصلها ساحلي بينما أطيات تكوين زور حوران أصلها بحري.

يعتبر معدن الكاؤولينايت المعدن الطيني الرئيس في هذه الرواسب مع كميات شحيحة من الألايت وطبقات مختلطة من الألايت والسمكتايت، ويختلط مع كوارتز وأكاسيد وهيدروكسيدات الحديد (معظمه غوثايت) واناتيس. يتراوح حجم حبيبات الطين في هذه الرواسب بين ناعم جدا وخشن ولدونتها بين فائقة ومتوسطة اللدونة، عدا طين الحسينيات الفلنتي اذ تنعدم فيه اللدونة. بينت الفحوصات أن أطيان تكويني الكعرة وعامج تتفتت عند غمرها في الماء خلال 2 – 4 دقائق بينما تحتاج أطيان تكوين الحسينيات وقت أطول لتتفتت. بين سلوكها الحراري أن الأطيان الحاوية على كميات قليلة من الشوائب تتحمل درجات حرارة أعلى اذ تستوي بدرجة حرارة 1200 °م. أما الأطيان الحاوية على كمية عالية من الشوائب مثل القلويات وأكاسيد الحديد تستوي فيها درجات الحرارة بين 1050 و 1100 °م. كما يختلف السلوك الحراري للطين الغريني عن بقية الاطيان اذ يتزايد انكماشها الخطي وكثافتها الكلية تدريجيا وقليلا عند ارتفاع درجة حرارة الحرق فيما تقل المسامية المفتوحة وامتصاص الماء بصورة أسرع.

تم تصنيف الأطيان الكاؤولينية للأغراض الصناعية الى صنفين: أطيان كاؤولينية بيضاء ($Al_2O_3 \geq 20\%$ و $Fe_2O_3 \leq 3\%$) وأطيان كاؤولينية ملونة ($Al_2O_3 \geq 20\%$ و $Fe_2O_3 \geq 3\%$). تم اجراء تحريات لاحقة على أطيان الكاؤولين في مناطق الكعرة والحسينيات وعامج لتخمين والتحقق من الأحتياطيات وتصنيفها بموجب كمياتها ونوعيتها ودرجتها وظروفها المنجمية، ونتجت عن هذه التحريات تقدير احتياطيات في منطقة الكعرة من الأطيان الكاؤولينية البيضاء والملونة (أصناف A و C_1 و C_2) حوالي 960 مليون طن وفي منطقة الحسينيات من الأطيان الكاؤولينية البيضاء والملونة (أصناف C_1 و C_2) 311 مليون طن وفي منطقة عامج من الأطيان الكاؤولينية الملونة (صنف C_2) 32 مليون طن وفي منطقة شمال شرق الحسينيات من الأطيان الكاؤولينية الفلنتية (صنف C_2) حوالي 10 مليون طن.

INTRODUCTION

Kaolinite {$Al_2Si_2O_5(OH)_4$} is a hydrous aluminosilicate of the phyllosilicate subclass. Two major kinds of kaolin clay are recognized, a primary or residual, which is considered as kaolin and secondary or transported, which is given various names such as kaolin clay, kaolinitic claystone, ball clay and many others. The kaolin clay is widely used in industry such as paper, ceramic, refractories, paint, rubber, pharmaceuticals and cosmetic, white cement and many other industries. The main consumption is paper, ceramics and refractories. All kaolin deposits at the Western and Southern deserts of Iraq are secondary and hence the term Kaolin clay will be used throughout this paper. The investigated clays are sedimentary (transported) except the flint clay, which is the product of kaolinite alteration during bauxitization.

Kaolinite is present throughout the geological column of the Western and Southern deserts of Iraq but it is dominant in the mudrocks of the Ordovician to Cretaceous systems. The most important exposed lithostratigraphic units containing kaolin-clay deposits are Ga'ara Formation (Permocarboniferous), Hussainiyat Formation (Lower Jurassic), Amij Formation (Middle Jurassic) and minor reserves of flint clay (associated with clayey bauxite), at the base of the Hussainiyat Formation in karsts developed in the Ubaid carbonates (Fig.1). Other exposed formations, such as Zor Hauran Formation (Upper Triassic), incorporate some thick impure kaolinitic horizons (Fig.1). Prospecting and explorations on kaolin clay however, focused on three formations, namely Ga'ara, Hussainiyat and Amij Formations (Fig.2).

Prospecting and exploration for kaolin clay as ceramic raw material started in 1960 by a group of Czech experts (Zurek and Knapp, 1960). Since then the search continued by the Iraq Geological Survey, though intermittently, exploring new and limited deposits. The investigations during the 60s and 70s of the last century focused on the white kaolin clay of the Ga'ara Formation at the Ga'ara Depression, such as Tel Afaif (Zurek and Knapp, 1960), Wadi Mulusi (Yousif and Jabbar, 1967), Samhat (Abboud and Raouf, 1972), Duekhla (Abdul Kadir and Santrucek, 1975), Telul Al-Humer (Elias and Abboud, 1987) and Wadi Al-Nijili (Al-Kindi and Mahmoud, 1987; Tamar-Agha and Mahmoud, 1989). Later, during the 80s and the 90s of the last century, extensive prospecting and exploration programs were carried out by the Iraq Geological Survey (Tamar-Agha, 1986; Tamar-Agha *et al*., 1991; Mahdi and Al-Hamad, 1990; Mahdi., 1993; Mahdi *et al*., 1993; Mahdi and Al-Dulaimi, 1996).

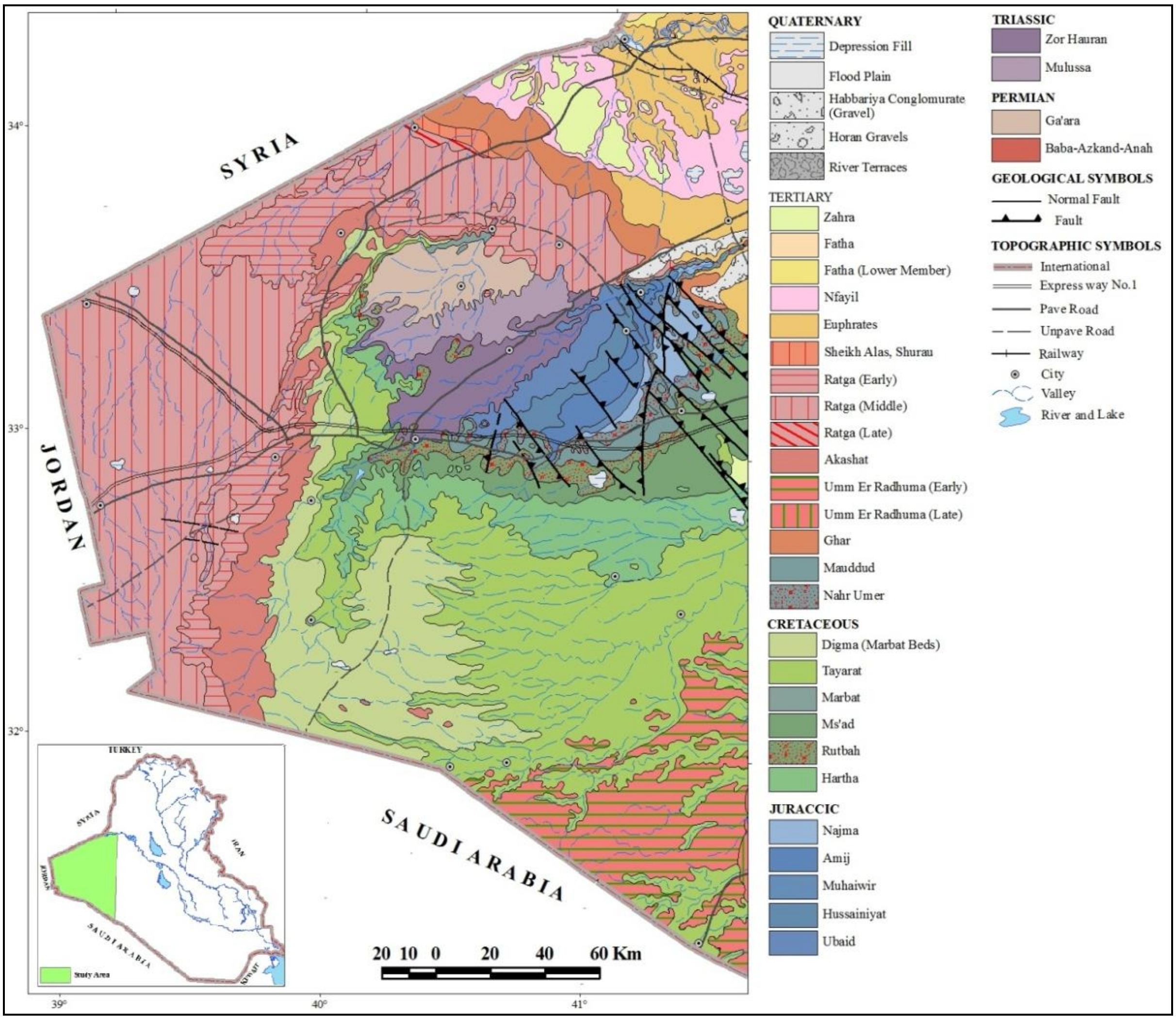


Fig.1: Geological map of the Western Desert of Iraq (from Sissakian, 2000)

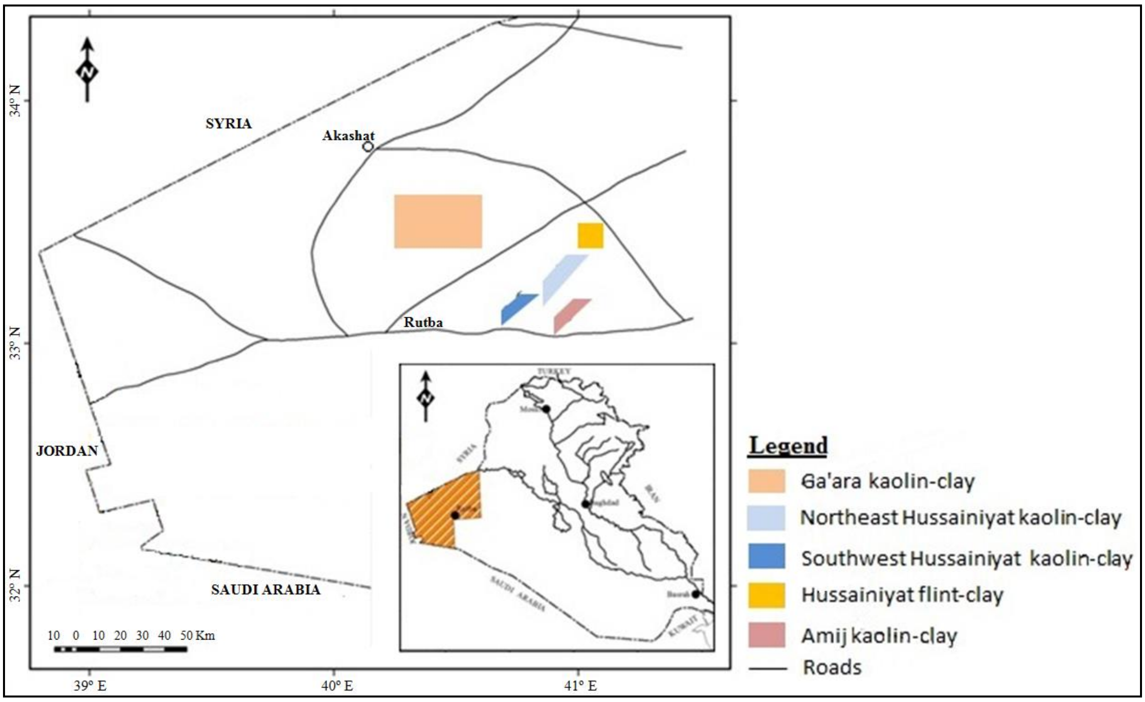


Fig.2: Location map showing the localities of kaolin-clay and flint-clay deposits in the Western Desert of Iraq

During the course of extensive prospecting and exploration on kaolin-clay deposits carried out by the Iraq Geological Survey extensive work was carried out in parallel on upgrading and technological tests. Laboratory experiments were carried out in order to assess their suitability for some industries such as ceramics, refractories, electroporcelain, paper, paints, alumina extraction, alum preparation and many others (Zurek and Knapp, 1960; Japan Consulting Institute- in Yousif and Jabbar, 1967; Mustafa, 1981; Al-Azzawi and Aly, 1983; Hammodi and Abdulla, 1987a; Hammodi and Abdulla, 1987b). In addition, many works were carried out by researchers at the universities, such as Al-Youzbaky (1989), Al-Kaysi (1989), Al-Mashaykhi (1991) and Tamar-Agha (1997) and at the research institutes such as Girgis *et al*. (1982), (Jindy and Ibrahim, 1982).The investigations on the Duekhla clay deposit was completed in 1975 (.Abdul Kadir and Santrucek, 1975) and its exploitation started in 1981. The Duekhla kaolin clay is mainly consumed in the manufacturing of white cement, ceramics and paper (as filler).

Later, the Iraq Geological Survey, after concluding the regional geological survey of the country, planned ambitious projects for detailed geological mapping (scale 1: 25 000), and they started at the Ga'ara depression. Two stages were carried out at the Ga'ara Depression, the first during 1983 and the second during 1986 – 1990. The work involved geological mapping, mineral prospecting and exploration of the mineral deposits including kaolin clay (Fig.3), quartz sand and ironstone. Tamar-Agha (1988) outlined the geological investigations on the Ga'ara kaolin clay focusing on their physical properties, chemical composition, grade, reserves and mining conditions. Laboratory experiments are carried out in order to assess their suitability for some industries such as ceramics, refractories, paper and paints. Some of these studies are carried out by Zurek and Knapp (1960), Japan Consulting Institute (in Yousif and Jabbar, 1967); Mustafa (1981); Girgis *et al.* (1982); Jindy and Ibrahim (1982); Al-Azzawi and Aly (1983); Hammodi and Abdulla (1987a); Hammodi and Abdulla (1987b); Al-Youzbaky (1989); Al-Kaysi (1989); Al-Mashaykhi (1991); Tamar-Agha (1997) and many others.

The aim of this article is to focus on the kaolin clay deposits at the Western Desert of Iraq, outlining their geological setting, mineralogy, chemistry, origin, physical properties, resources, mining conditions, technological test and industrial uses.

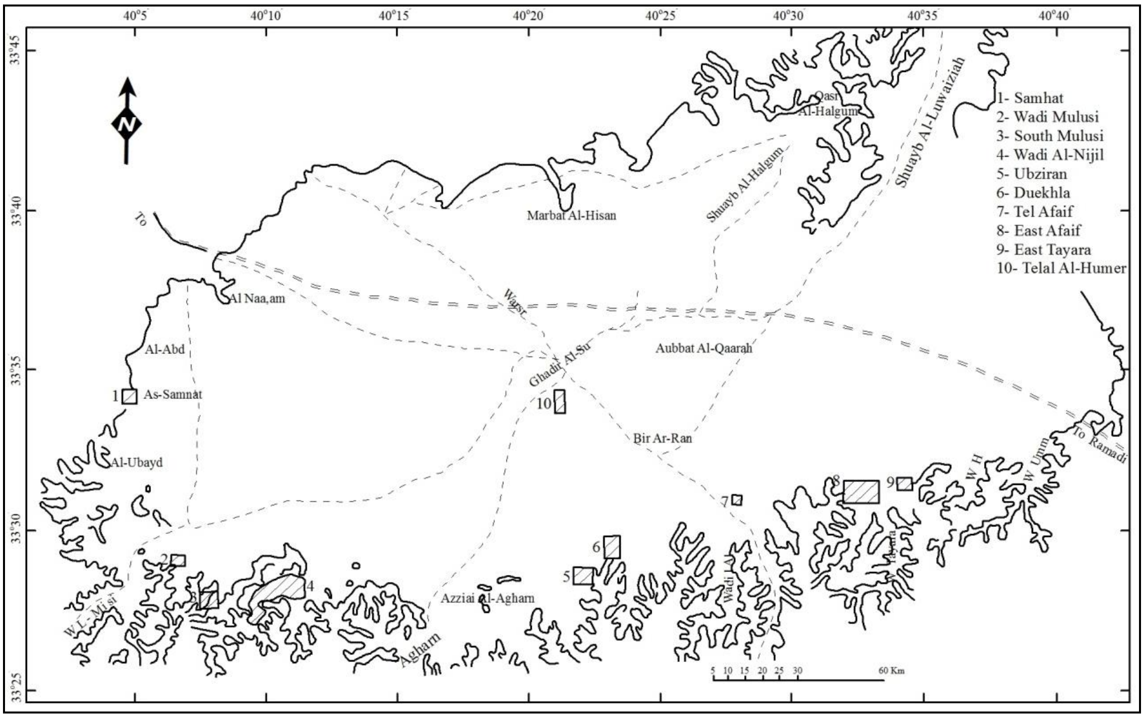


Fig.3: Location of kaolin deposits in Ga'ara Depression

Prospecting and explorations at the Hussainiyat area include two sites, namely the Northeast and Southwest Hussainiyat (Fig.2). Reserves of both white and coloured kaolin clays are estimated in addition to grade and mining conditions (Mahdi and Al-Hamad, 1990 and Mahdi, 1993). Prospecting and exploration was carried out at Amij area and relatively moderate reserve of paralic coloured kaolin clay is estimated (Mahdi *et al*., 1993). Flint clay was explored at the Northeast Hussainiyat area associated with the karst bauxite and bauxitic clay deposit (Mustafa *et al*., 1994).

GEOLOGICAL SETTING

The investigated area is part of the Western Desert sector of the Arabian Plate Inner Platform, according to the scheme proposed by Fouad (2014). Outcrops of the Ga'ara Formation are restricted to the Ga'ara depression whereas the Hussainiyat and Amij exposures are about 50 kilometers east of the depression (Fig.1).

The Ga'ara Depression is a suboval erosional feature extending in an E – W direction and located about 50 Km north of Rutba Town, in the Western Desert of Iraq (Fig.1). The depression is about 2, 200 Km^2 (about 73 × 30 Km) and is a pompous feature of the Western Desert of Iraq. It is known to have resulted from the erosion of the core of a shallow dome, but later studies reveal that such dome does not exist (Tamar-Agha *et al*., 1997). Instead, the old strata (Ga'ara Formation) crops out in the central part of the depression overlain by Upper Triassic carbonates (Mulussa Formation) at the southern rim of the depression. These strata are part of an old monocline dipping very gently (less than one degree) in a SSW direction.

The other rims constitute another young monocline with younger strata (Upper Cretaceous – Paleogene) dipping very gently northwards.

The Ga'ara Formation is overlain in the south and southwest by Mulussa Formation (Upper Triassic-dolostones and marl). In the west by Rutbah Formation (Cenomanian – ?Turonian-sandstone). In the northwest and north it is overlain by the Digma Formation (Upper Cretaceous-carbonates, phosphorites and marl) and Marbat Beds (Upper Cretaceous-clastics), in the northeast by the Akashat Formation (Paleocene-phosphorites, carbonates and mudrocks) and in the east and southeast it is covered by the Ratga Formation (Lower Eocene-limestone) (Tamar-Agha, 1991).

The Ga'ara Formation is the oldest exposed lithostratigraphic unit in the western sector of Iraq. It belongs to the Arabian Plate Tectonostratigraphic Megasequence (AP5) of Sharland *et al.* (2001), which represents Late Stephanian to Ufimian age and later modified by Jassim (2006) to Westphalian – Ufimian (Syn-Hercynian). The exposed part of this formation exceeds 100 metres. Palynological studies showed that the age of this formation is Lower Permian (Raee Al-Balha, 1989). The Ga'ara Formation comprises repeated successions of sandstone and mudstone (silty claystone and claystone). These successions represent fluvial systems (Tamar-Agha, 1986).

The sandstones form about 35% of the column in the southern part of the Ga'ara Depression and about the total thickness in the north. The northern part represents a lower stratigraphic unit named Rumliya Unit (Tamar-Agha *et al*., 1997). They are generally white to beige or variegated. The mudstone forms the major lithology in the upper part of the Ga'ara Formation, especially in the southern part of the depression. The colour is variable ranging from white, pale grey, black, yellow, red, violet, etc. The mudstones are soft to medium tough, ferruginous in places (reaching up to 56% Fe_2O_3). The iron oxides and hydroxides are present as pisolites, oolites, concretions and stains. Silt and sand admixtures are commonly found increasing especially in the lower part of the mudstones. Plant debris and rootlets are frequent. In some cases they are rich in organic matter and even with pyrite concretions. The mudstone represents deposition in river overbanks, mud plugs, abandoned channels and oxbow lakes (Tamar-Agha, 1986 and 1991).

The Hussainiyat Formation crops out along NE – SW trending arced belt. It belongs to the Arabian Plate Tectonostratigraphic Megasequence (TMS – AP6) of Sharland *et al.* (2001), which represents Mid-Permian, to Early Jurassic age. The exploration area was part of the equatorial zone during the Early Jurassic (Sharland *et al*., 2001). The Hussainiyat Formation unconformably overlies the Ubaid Formation. It consists of two members, a lower siliciclastics member and an upper carbonates member. The thickness of the Hussainiyat Formation ranges from 10 to 120 metres: siliciclastic unit 21 to 65 meters thick and less than 28 meters of the carbonate unit (Al-Mubarak, 1983). The age of the Hussainiyat Formation is rather controversial. Some workers accepted a Liassic age based on its stratigraphic position between the Ubaid and Amij Formations (Buday and Hak, 1980; Karim and Ctyroky, 1981, Jassim *et al*., 1984; Jassim *et al*., 2006). Al-Jibouri (1998) proposed a Liassic age (Hettangian-Pliensbachian) on palynological evidence. Hassan (1985) proposed a Bajocian age based on some invertebrate fossils.

The Hussainiyat Formation comprises two units: an upper carbonate unit (mostly dolomite) and a lower siliciclastic – ferruginous unit. The siliciclastics consist of two contrasting lithological packages. The northern exposures comprise alternating mature sandstone and kaolinitic mudrocks passing southwards to ferruginous kaolinitic mudrocks and ironstone (Al-Bassam and Tamar-Agha 1998). The Amij Formation also crops out along NE – SW trending arced belt and it is supposedly belongs to the Arabian Plate Tectonostratigraphic Megasequence (AP7) of Sharland *et al.* (2001), where the study area was in the equatorial zone also. It unconformably overlies the Hussainiyat Formation. The Amij Formation consists of two units, a lower siliciclastics unit (15 to 20 metres thick) and an upper carbonate unit (15 to 30 metres thick) (Al-Naqib *et al*., 1986). The age of this formation is also controversial but Middle Jurassic age is accepted (Jassim *et al*., 2006). The lower unit consists of repeated coarsening-upwards successions consisting of mudstones and sandstones. These successions represent paralic environments such as deltas and coastal deposits (Al-Hadithi, 1989). The sandstones are generally white to cream whereas the mudstones are reddish brown. The mudstones are believed to represents deposition in prodelta, on-delta and mud flats (Al-Hadithi, 1989; Mahdi *et al*., 1993).

DEPOSITIONAL HISTORY AND PROVENANCE

The Ga'ara Formation comprises repeated fining-upwards successions (Fig.4) consisting of sandstone and mudstone (silty claystone and claystone). Facies analysis reveals that these successions are active valley, point-bar accretion, abandoned valley, mud plugs, river overbanks and oxbow lakes lithofacies (Tamar-Agha, 1986). These lithofacies collectively, supported by sandstone percentage maps, represent high-sinuosity (meandering) stream system. The kaolin-clay deposits are deposited in river overbanks, mud plugs, abandoned channels and oxbow lakes.

Detailed petrographic studies of the sandstones of the Ga'ara Formation carried out by many workers (such as Tobia, 1983; Sadiq, 1985 and Tamar-Agha, 1986) showed that they are quartz arenites and in average more than 95% of the framework fragments is quartz (mostly monocrystalline quartz). The quartz grains are subangular to subrounded, fine to medium in size and rarely very fine, coarse or gravelly. According to the petrographic and heavy mineral analysis the source rocks consist basically of granitoids (acid and intermediate plutonic rocks and gneisses) and sedimentary rocks (especially siliciclastics). Following the consolidation of the Arabo-Nubian Shield and its accretion to the margin of Gondwana, a long period of relative stability prevailed, and much of the Paleozoic is dominated by the deposition of widely spread sheets of siliciclastic sediments deposited in epicontinental seas that spread across much of the Middle East (Sharland *et al*., 2001).

Evaluation of source rocks that furnished sediments to the study area requires some knowledge of the extent of sediment recycling, in order to distinguish proximity from the ultimate source. The superabundance of quartz, richness of ultrastable heavy minerals and high degree of rounding of framework fragments support the recycling of the sediments of the Ga'ara Formations. These rocks suffered from moderate weathering in the source area, where the feldspars were almost completely altered in wet and tropical climate, within an almost flat terrain to produce large amount of clay and sand particles. The clay is mostly kaolinite with subordinate illite and mixed-layer illite-smectite whereas the sand is mostly quartz and almost devoid of feldspars. The kaolinite particles are frequently coated with iron oxides and hydroxides (Tamar-Agha, 1986 and 1991).

The weathered detritus were then transported by rivers as quartz-rich sand and kaolinite-rich clay. The rivers sorted these sediments remarkably well, depositing the sand in the interweaving channel course whereas the fines (i.e. silts and clays) were deposited in the interchannel flats (overbanks and ox-bow lakes) or in the abandoned channels. Facies analysis of the Ga'ara Formation, particularly at the southern rim of the depression, showed that it comprises sandstones and mudstones in repeated fining-upwards successions, which characterize fluvial deposition. This rhythmic nature results from both lateral channel migration (point-bar sequence) and vertical channel aggradation, inferring meandering rivers (Tamar-Agha, 1986).

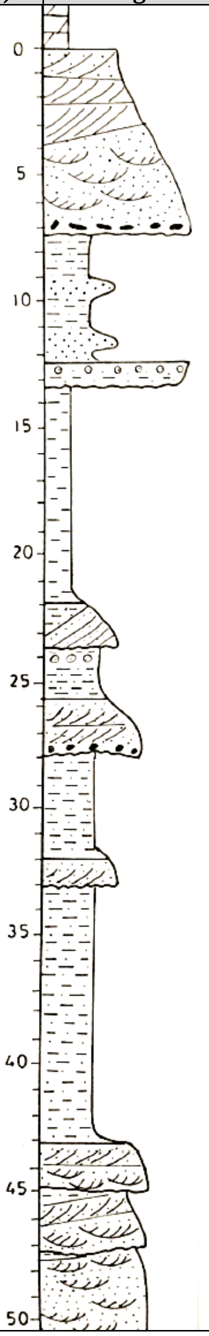
Thick (m)	Lithological log	Description	Interpretation
		Mulussa Formation/ mostly dolostone	Shallow marine, tidal deposits
		Sandstone, while and cream, the base with some exotic gravel, then trough and tabular **cross** bedded	Channel floor and point bar deposits
		Silty claystone and sandstone, pink mottled with yellow	Flood plain and crevasse splay deposits
		Clayey sandstone pink, pisolitic iron	Channel deposits
		Claystone, pink, mottled with yellow, occasional rootlets	Flood plain deposits
		Sandstone, white and pink, lens	Point bar deposits
		Silty claystone, pink and violet pisolitic	Pedogenized floodplain deposits
		Sandstone, reddish brown ferruginous	Channel floor and point bar deposits
		Silty claystone cream and pink mottled with yellow, iron concretions and crusts	Flood plain deposits
		Sandstone reddish brown	Point bar deposits
		Silty claystone and claystone, grey and pink mottled with yellow, plant debris frequent	Flood plain deposits
		Sandstone, reddish brown channeled, trough and tabular cross bedded, their thickness decrease upwards	Alternating channel floor and point bar deposits

Fig.4: Columnar section of the Ga'ara Formation at the Ga'ara Depression (after Tamar-Agha, 1991)

The clay was further decayed at the depositional site, i.e. matured by pedogenic processes transforming the majority of illite to kaolinite and transforming some of the kaolinite to gibbsite and poorly-ordered kaolinite. Iron oxides were mobilized by both plant and groundwater activity to be concentrated as ferricrete structures. It may have also been affected by later diagenetic processes of mobilization and reprecipitation or redeposition.

Facies analyses of the Hussainiyat Formation indicate that deposition occurred in high-sinuosity (meandering) stream deposits (Al-Bassam and Tamar-Agha, 1998). Later, Tamar-Agha and co-workers (2016) recognized six facies from the Hussainiyat Formation using Miall’s (1978) terminologies and facies code. In general, the studied sections portray an overall fining-upward succession with bipartite lithologies constituting sandstone and mudrocks which are vertically stacked (Fig.5). Each succession begins with coarse channel lag deposits with an erosional scour base overlain by cross-bedded sandstone and culminates with mudrocks. The sandstone that forms the basal unit shows an upward decrease in grain size accompanied by bedform change. The lower part of the sandstone is usually trough cross-bedded which shows an upward reduction in cross-bed set size whereas the upper part is planar tabular cross-bedded. Cross-laminations are not recorded. This fining-upwards succession represents the classic model for high-sinuosity (meandering) river system which has been proposed by Allen (1970). The succession begins with lag deposits, followed by cross-bedded channel bars and laterally accreted point-bar sandstone, which is eventually replaced upward by overbank mudrocks, i.e. vertically accreted floodplain deposit.

The sandstones are generally white to beige or variegated. The mudstone forms the major lithology in the Hussainiyat Formation and their colour are variable ranging from white, pale grey, black, yellow, red, violet, etc. The mudstones are soft to medium tough, ferruginous in places (reaching up to 56% Fe_2O_3).The iron oxides and hydroxides are present as pisolites, oolites, concretions and stains. Silt and sand admixtures are commonly found increasing especially in the lower part of the mudstones. Plant debris and rootlets are frequent. In some cases they are rich in organic matter and even with pyrite concretions. The mudstone represents deposition in river overbanks, mud plugs, abandoned channels and oxbow lakes (Mahdi and Al-Hamad, 1990; Mahdi *et al*., 1993; Mahdi and Al-Dulaimi, 1996 and Al-Bassam and Tamar-Agha, 1997).

Petrographic studies revealed that the framework fragments are in general similar to the sandstone of the Ga'ara Formation, but there is a slight difference in their primary textures. The majority of the grains of the Hussainiyat Formation sandstones are also subangular to subrounded, like the Ga'ara sandstone, but the grains of the former are more angular and coarser than those of the latter. Sandstones of both formations are almost devoid of matrix and consist mostly of quartz grains ($\geq$ 95%), i.e. physically and mineralogically super-mature (Tamar-Agha *et al*., 2016). Accordingly, these textural features discount the idea that the Hussainiyat siliciclastics are derived from the Ga'ara siliciclastics.

Petrographic analysis reveals that sandstones of the Hussainiyat and the Ga'ara formations are quartz arenites with superabundance of quartz, indicating derivation from quartz-rich source rocks (Tamar-Agha *et al*., 2016). They believed that the association of quartz arenites with thick kaolinitic mudrocks, in both formations indicates that the source rocks are rich in feldspars too. The feldspars are almost absent as very little is left in the framework fragments, which means that they were either syndepositionally hydrolyzed at the source area or hydrolyzed at earlier times and the sediments were recycled. The latter is favored for the reasons mentioned earlier. Intense chemical weathering is expected during the

Jurassic time since the area forms part of the equatorial zone. This supports the recycling of sediments. The suite of heavy minerals such as rutile, tourmaline and zircon reveals derivation from alkaline igneous rock source, pyroxenes and opaques (mostly chromite, ilmenite and magnetite) from basic and intermediate igneous rock source and staurolite and epidote from metamorphic rock source. However, since the majority of the ultrastable minerals are rounded, it indicates that the recycling (i.e. sedimentary source rock) is predominant.

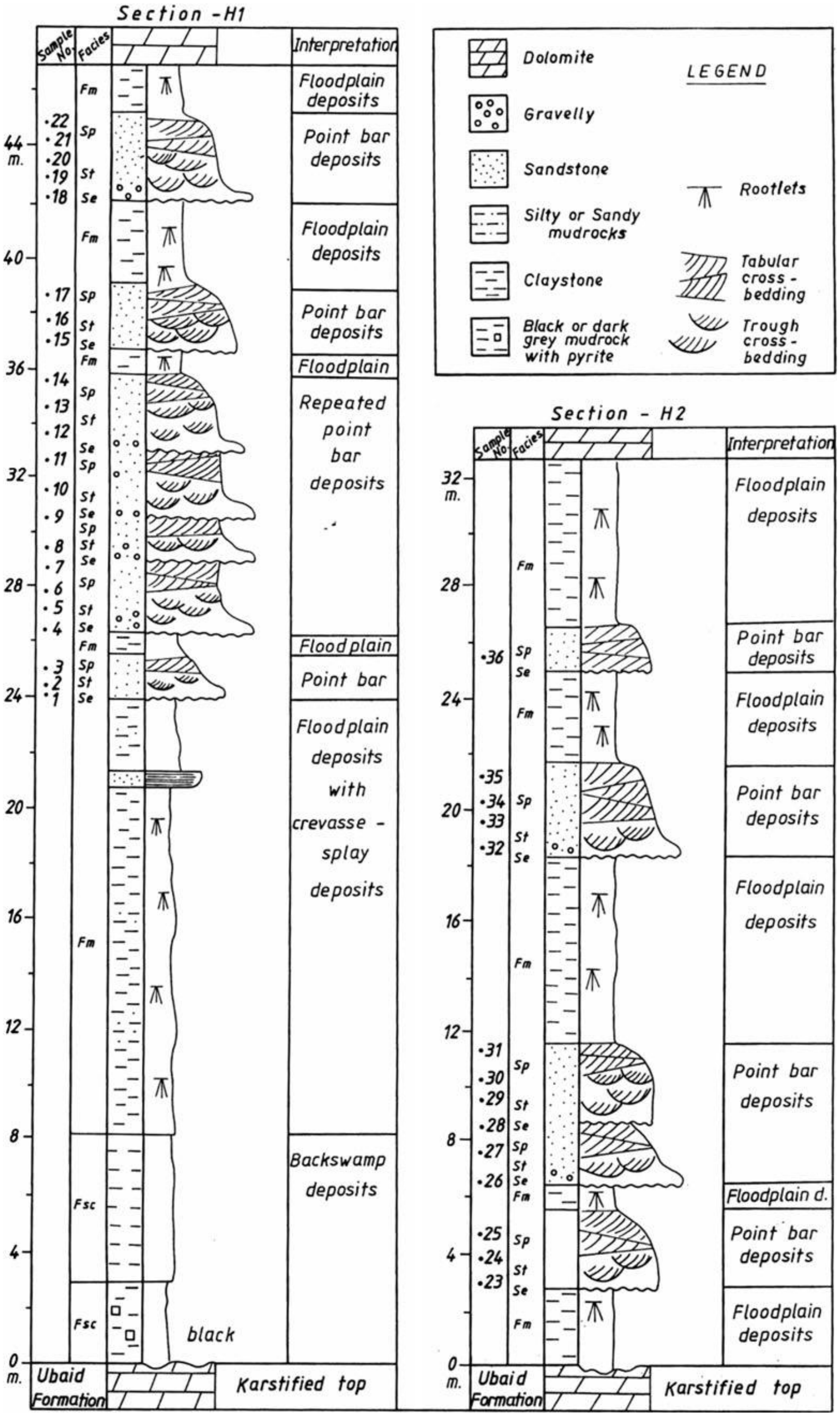


Fig.5: Columnar section of the Hussainiyat Formation (after Tamar-Agha *et al*., 2016)

Facies analyses of the siliciclastic unit of the Amij Formation indicate that deposition took place in lobate-constructive fluvial deltas (Al-Hadithi, 1989). He recognized five lithofacies subdivided into nine sublithofacies, which are nested in coarsening-upwards manner (Fig.6). The lithofacies are grouped into four facies associations, namely prodelta, distributary mouth-bar, distributary channel and interdistributary bays. Al-Hadithi (1989) concluded that the climate during the deposition of the Amij Formation was dry based on the presence of evaporites and the absence of coal horizons.

Kettanah and Ismail (2016) believe that the expected dominant source of the deposits (sandstones) of the Amij Formation is most probably the felsic igneous and metamorphic complexes of the Arabian Shield. These detrital materials were transported by rivers northwards to be deposited in paralic environments. Rigorous and comprehensive analyses of the heavy minerals led them to conclude the source area is currently located about 600 Km to the south of the studied area. The rivers headed northwards moving and sorting the detritus and eventually deposited them in delta mouth and along beaches of the Neo-Tethys Ocean under passive margin tectonic setting. During deposition the sediments were further sorted out by ocean waves as black sand concentrations.

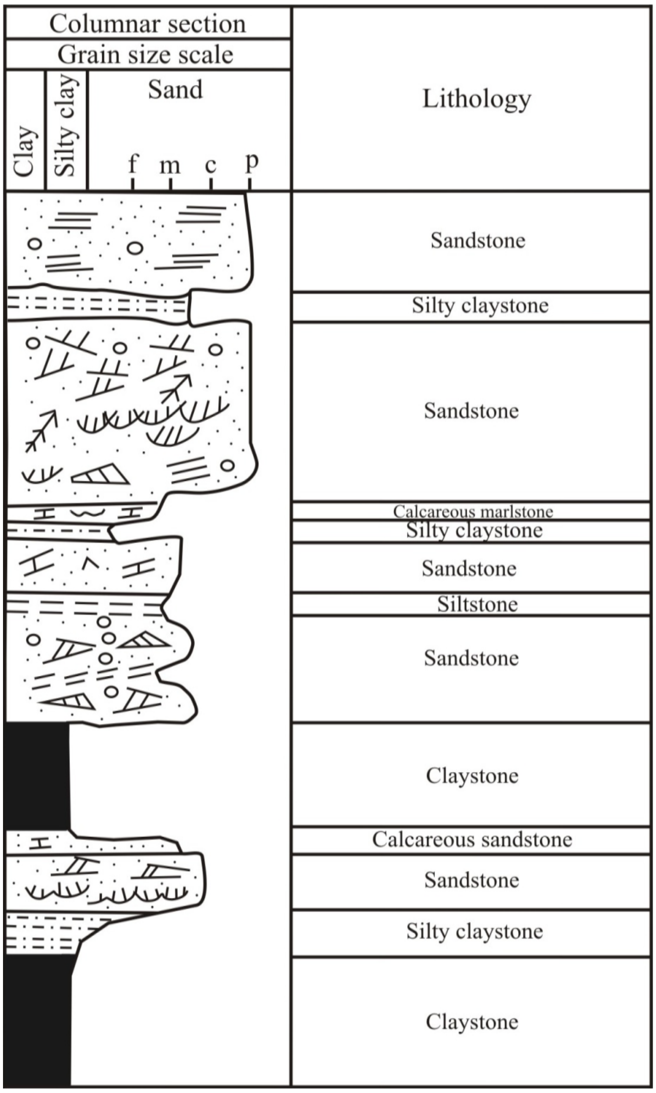


Fig.6: Columnar section of the Amij Formation (after Al-Hadithi, 1989)

CHARACTERIZATION OF THE KAOLIN-CLAY

Tamar-Agha (1997) collected nine representative bulk samples from seven localities representing the three formations (Ga'ara, Hussainiyat and Amij). The collected samples represent operating mines, and identified and inferred kaolin-clay reserves (Fig.7 and Table 1). About 10 kilograms were taken from mine faces, boreholes or trenches to represent the whole deposits. The samples were crushed, well mixed and divided into small portions by quartering to get representative samples for physical tests, mineralogical and chemical analysis. They were then assessed for utilization in many industries.

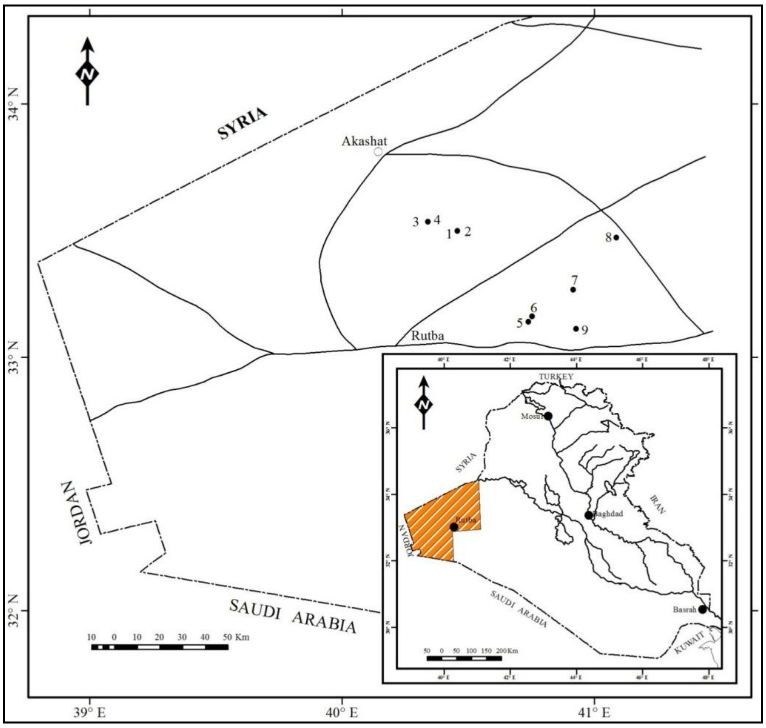


Fig.7: Map showing locations of the collected representative kaolin-clay samples: **1)** Duekhla clay, **2)** Coloured Duekhla clay, **3**) Sufi clay, **4)** Silty Sufi flint clay, **5)** Lower Hussainiyat clay, **6)** Upper Hussainiyat clay, **7)** White Hussainiyat clay, **8)** Hussainiyat flint-clay and **9)** Amij clay (after Tamar-Agha, 1997)

Table 1: Deposit number (refers to deposit location in Figure 7), name of clay deposits, their stratigraphic units, reserve categorization and source of samples (after Tamar-Agha, 1997)

Deposit No.	**Name of Deposit**	**Formation**	**Remarks**
1	Duekhla clay	Ga'ara	Identified reserve – Duekhla kaolin mine
2	Coloured Duekhla clay	Ga'ara	Identified reserve – floor of the Duekhla kaolin mine
3	Sufi clay	Ga'ara	Identified reserve – trenches and boreholes
4	Silty Sufi clay	Ga'ara	Identified reserve – trenches and boreholes
5	Lower Hussainiyat clay	Hussainiyat	Identified reserve – floor of the Hussainiyat ironstone mine
6	Upper Hussainiyat clay	Hussainiyat	Identified reserve – roof of the Hussainiyat ironstone mine
7	White Hussainiyat clay	Hussainiyat	Inferred reserve – trenches only
8	Hussainiyat Flint clay	Hussainiyat	Identified reserve – Hussainiyat flint clay mine
9	Amij clay	Amij	Inferred reserve – trenches only

- **Mineralogy**

– **X-ray Diffractometry (XRD):** The XRD analysis of the mudstones of the Ga'ara, Hussainiyat and Amij Formations were carried out using the powder for the bulk sample and oriented mounts for the -2µm fraction. The first mount was left air-dried (untreated) whereas the other two were either treated with ethylene glycol or heated at 550 °C for two hours. The X-ray diffractograms revealed that the major clay mineral present is kaolinite with minor proportions of illite and mixed-layer illite-smectite (Figs.8, 9 and 10). The other main admixtures present are quartz, iron oxyhydroxides (mostly goethite) and anatase.

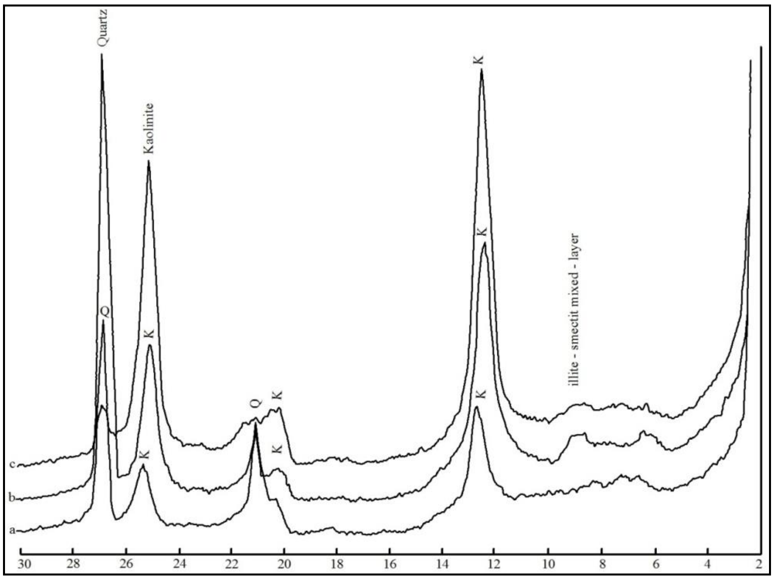


Fig.8: XRD diffractograms of the Ga'ara clays. **a-** Sufi clay, **b-** Silty Sufi clay and **c-** Duekhla kaolin clay (after Tamar-Agha, 1997)

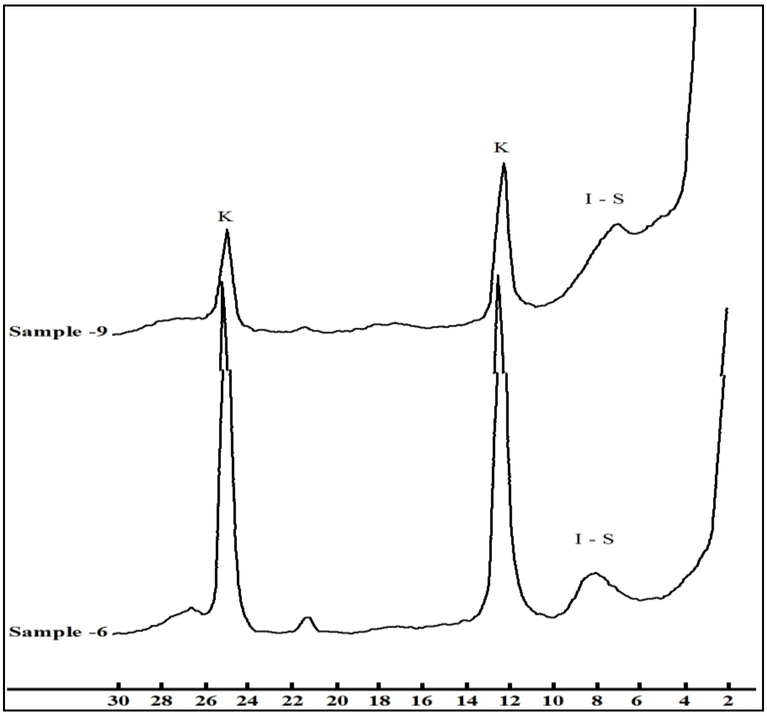


Fig.9: XRD diffractograms of the Hussainiyat and Amij clays (after Tamar-Agha, 1997)

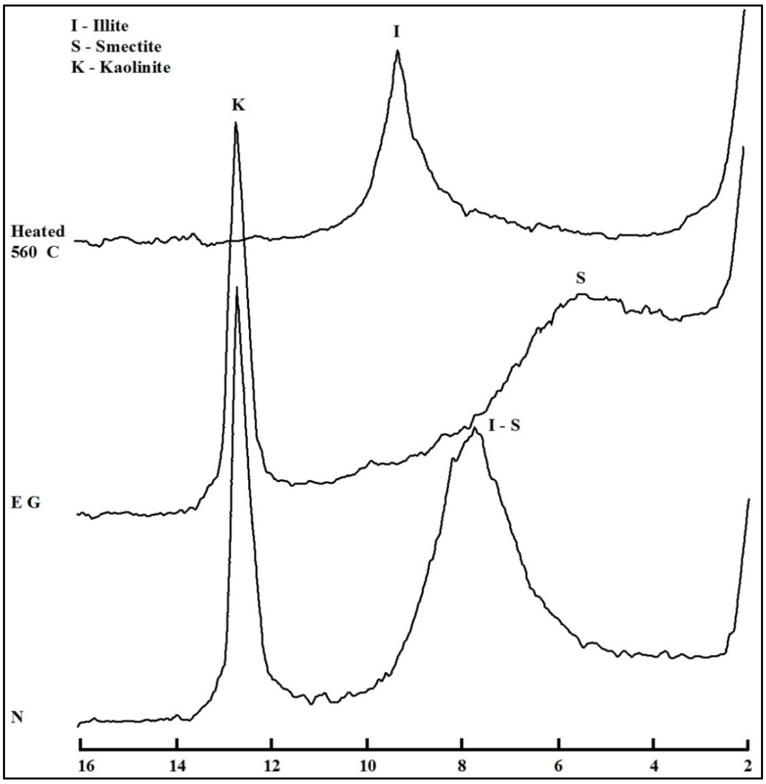


Fig.10: XRD diffractograms of white Hussainiyat clay (sample 7),
(after Tamar-Agha, 1997)

– **Differential Thermal Analysis (DTA) and Thermal Gravimetry (TG):** The DTA and TG analysis support the XRD results as the shape of their curves are not greatly affected by the minor components and represent a typical kaolinite curves (Fig.11). DTA-TG study is useful in the mineral identification of the clays as well as it sheds light onto their behavior during firing. Four major peaks are recognized: the first peak is endothermic and lies between 90 – 150 °C resulting from the removal of the non-constitutional water in the kaolinites and the loss of a water molecule in the mixed-layer illite-smectite; the second peak is endothermic and lies between 320 – 410 °C representing a combination of peaks resulting from the loss of structural water of mixed-layer illite-smectite and illite (320 – 335 °C) and dehydroxilation of goethite (335 – 410 °C); the third peak is endothermic and is the most prominent occurring at the temperature range between 530 – 570 °C which corresponds to the expulsion of water from the kaolinite lattice; the fourth peak is exothermic and lies between 940 and 1000 °C resulting from the formation of mullite, spinal and cristobalite.

- **Chemical Composition**

The chemical analyses were carried out using atomic absorption spectrometry (AAS) for Al_2O_3, Fe_2O_3, TiO_2, Na_2O, K_2O, CaO and MgO and gravimetric method for SiO_2 and Loss on Ignition (L.O.I). L.O.I is calculated after firing to 1000 °C. The chemical analyses of the nine explored kaolin clay deposits are given in Table 2. The analyses are recalculated into mineral percentages with the aid of the XRD results (Table.2) and plotted on ternary diagrams suggested by Fabbri and Fiori (1985) in order to classify raw materials for industrial ceramic bodies (Fig.12). The main constituents of the investigated clays are SiO_2, Al_2O_3 and L.O.I. Significant amount of Fe_2O_3 is recorded in the samples ranging from 0.91 – 9.70%, whereas titania is approximately constant ranging from 1.12 – 2.34%. The latter is usually higher in the Hussainiyat clays than in the Ga'ara and Amij kaolin clays. The total alkalies (Na_2O, K_2O, CaO and MgO), which behave as fluxes during firing, are generally low in the Ga'ara and Hussainiyat kaolin clay (0.86 – 3.17%) but are considerably higher in the Amij kaolin clay (9.18%).

The alumina content of the investigated clays ranges from 20.8 – 35.4%. On the basis of alumina content, the clays can be classified into fat (≥ 30 Al_2O_3), moderately fat (25 – 30% Al_2O_3) and lean (20 – 25% Al_2O_3). Accordingly white Duekhla, white Hussainiyat and Hussainiyat flint kaolin clays are fat clays, Sufi kaolin clay is moderately fat and the other five samples are lean clays.

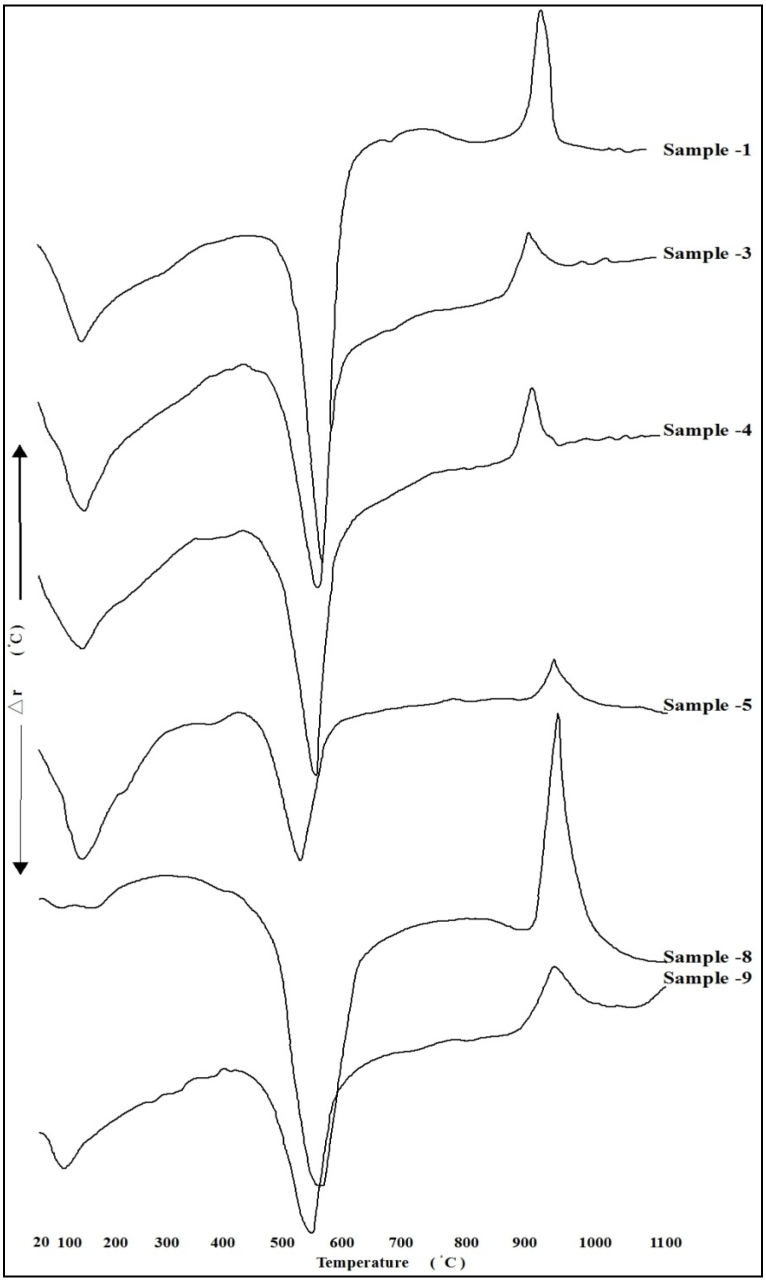


Fig.11: DTA curves of the studied clays (after Tamar-Agha, 1997)

Table 2: Chemical constituents of the nine studied samples and their calculated mineralogy (after Tamar-Agha, 1997)

	Sample number								
Constituents	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SiO_2	48.3	54.4	58.6	65.3	47.8	45.6	45.3	46.2	45.9
Al_2O_3	34.6	24.9	25.3	20.8	23.1	24.9	31.1	35.4	24.2
Fe_2O_3	1.02	1.17	2.3	2.15	9.2	9.7	3.43	0.91	7.87
TiO_2	1.15	1.31	1.12	1.22	1.73	1.67	2.34	1.85	1.32
Na_2O	0.32	0.42	0.41	0.39	0.72	1.39	1.73	0.22	0.79
K_2O	0.61	0.73	1.31	0.97	0.55	0.41	0.11	0.21	1.12
CaO	0.18	0.14	0.41	0.36	0.29	0.30	0.31	0.16	5.63
MgO	0.40	0.51	0.82	0.62	1.61	0.93	0.43	0.27	1.67
L.O.I	13.05	10.7	8.9	7.6	14.6	14.1	14.7	14.1	11.32
Illite	4.3	5.8	14.2	9.4	3.4	1.4	-	-	11.7
Kaolinite	85.9	60.0	55.3	47.0	38.4	54. 4	74.5	87.5	38.1
Smectite	-	-	-	-	38.0	18.3	10.8	6.75	33.0
Quartz	5.7	23.9	26.1	39.0	6.1	9.3	4.7	2.0	3.1
Goethite	-	5.9	1.9	1.4	7.1	8.9	2.3	-	5.6
Anatase	1.1	1.4	1.1	1.2	1.72	1.66	2.34	1.85	1.3
Halite	0.5	0.8	0.8	0.7	1.4	2.3	3.04	0.4	1.5

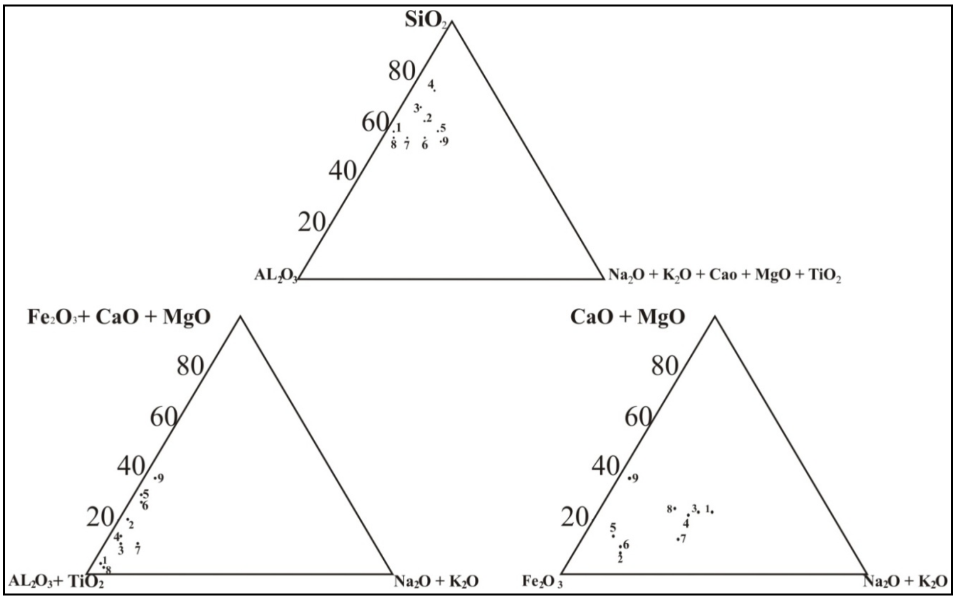


Fig.12: Ternary diagrams of different chemical and members of the studied clays (after Tamar-Agha, 1997)

- **Physical Properties**

– **Particle Size:** Particle size analysis was determined by the hydrometer method as specified in the ASTM standard specification C775-79T and represented in Table (3). The scheme of clay classification according to particle size was proposed by Mustafa (1981) and modified by Tamar-Agha (1997). They used the percentage of the size fraction coarser than 20 μm as basis for their classification and they suggested four classes as follows: very fine (<5%), fine (5 – 10%), medium (10 – 15%) and coarse (15 – 50%). According to this scheme of classification, three kaolin clays (white Duekhla, coloured Duekhla and Amij Clays) are very fine clays, three kaolin clays (Sufi, Lower Hussainiyat and white Hussainiyat Clays) are fine clays and two kaolin clays (silty Sufi and Upper Hussainiyat Clays) are coarse clays.

– **Plasticity Index (P.I.):** Plasticity index (or Atterberg's limits) is determined as specified in the ASTM standard D424-59. Plasticity values showed wide range of variation ranging from 11 to 30 (Table 3). Ga'ara clays show higher plasticity than Hussainiyat and Amij clays. Clays for ceramic industries were classified by Budnikov (1964), on the basis of plasticity index, into five groups. According to this classification the white and coloured Duekhla clays are super-plastic, Sufi and silty Sufi kaolin clays are medium plastic. The Hussainiyat and Amij kaolin clays are medium plastic except the white Hussainiyat clay is moderately plastic and the Hussainiyat flint clay is non-plastic. Plasticity values are intimately related to particle size distribution and mineralogy. The finer the particle size and the higher content of phyllosilicates the higher values of plasticity index such as white Duekhla kaolin clay.

– **Nature of Slaking.** Nature of slaking was carried out on lumps of few centimetres in diameter. The lumps were placed in a beaker filled with water and the time required for their disintegration was recorded. Nature of slaking is tested in order to investigate the binding strength of the clay particles and the degree of consolidation of the clay mass (Table 3). The Ga'ara and Amij clays disintegrate within 2 – 4 minutes after immersion in water whereas the Hussainiyat kaolin clays require longer time to disintegrate ranging from several minutes to unaffected (Table 3).

Table 3: The percentage of materials contained between two size fractions, below two microns and one microns, size class, Plasticity Index and nature of slaking. (Deposit number is as in Figure 7) (after Tamar-Agha, 1997)

Deposit No.	> 20	10 – 20	5 – 10	2 – 5	< 2	< 1	Size Class	Plasticity Index	Nature of Slaking
	µm								
1	4.1	2.8	2.5	7.3	82.9	68.9	Very fine	30	Quick
2	3.3	1.6	2.1	9.4	83.6	73.1	Very fine	31	Quick
3	5.8	4.5	7.2	15.2	67.3	57.0	Fine	23	Quick
4	17.1	12.0	11.1	10.9	48.9	35.4	Coarse	17	Quick
5	7.0	4.5	5.0	7.0	76.5	74.0	Fine	24	Very slow
6	22.0	3.5	2.5	5.0	67.0	63.0	Coarse	24	Moderate
7	7.5	7.0	4.5	4.2	76.8	74.1	Fine	11	Slow
9	0.4	1.6	8.0	13.0	77.0	67.0	Very fine	15	Quick

- **Thermal Behavior**

Thermal behavior of these kaolin clays were investigated at temperatures 1000 to 1250 °C. For this purpose briquettes (8 × 4 × 1 cm) were prepared by semi-dry molding (8 – 10% moisture content and 250 kg/cm^2), oven dried (105 °C for 24 hours) then fired to 1000, 1050, 1100, 1150 and 1200 °C (temperature rise 50 °C/hour and 2 hours soaking time. The fired bodies were analyzed for linear shrinkage, open porosity, water absorption and bulk density. These parameters were plotted as firing diagrams (Fig.13). It seems that chemical composition of the raw clay controls the shape of these curves. In general, clays with little impurities sustain higher temperatures and hence physical properties of the test briquettes level off at temperatures as high as 1200 °C. On the other hand, physical properties of clays containing high impurities, such as alkalies and iron oxides, level off at temperatures ranging from 1050 to 1100 °C, depending on the content of their impurities. Thermal behavior of the silty Sufi kaolin clay differs from the rest of the clays as the linear shrinkage and bulk density show gradual and very slight increase with rise of firing temperature (without noticeable leveling off) whereas its open porosity and water absorption decrease with steeper gradient. This behavior can be attributed to its high quartz content.

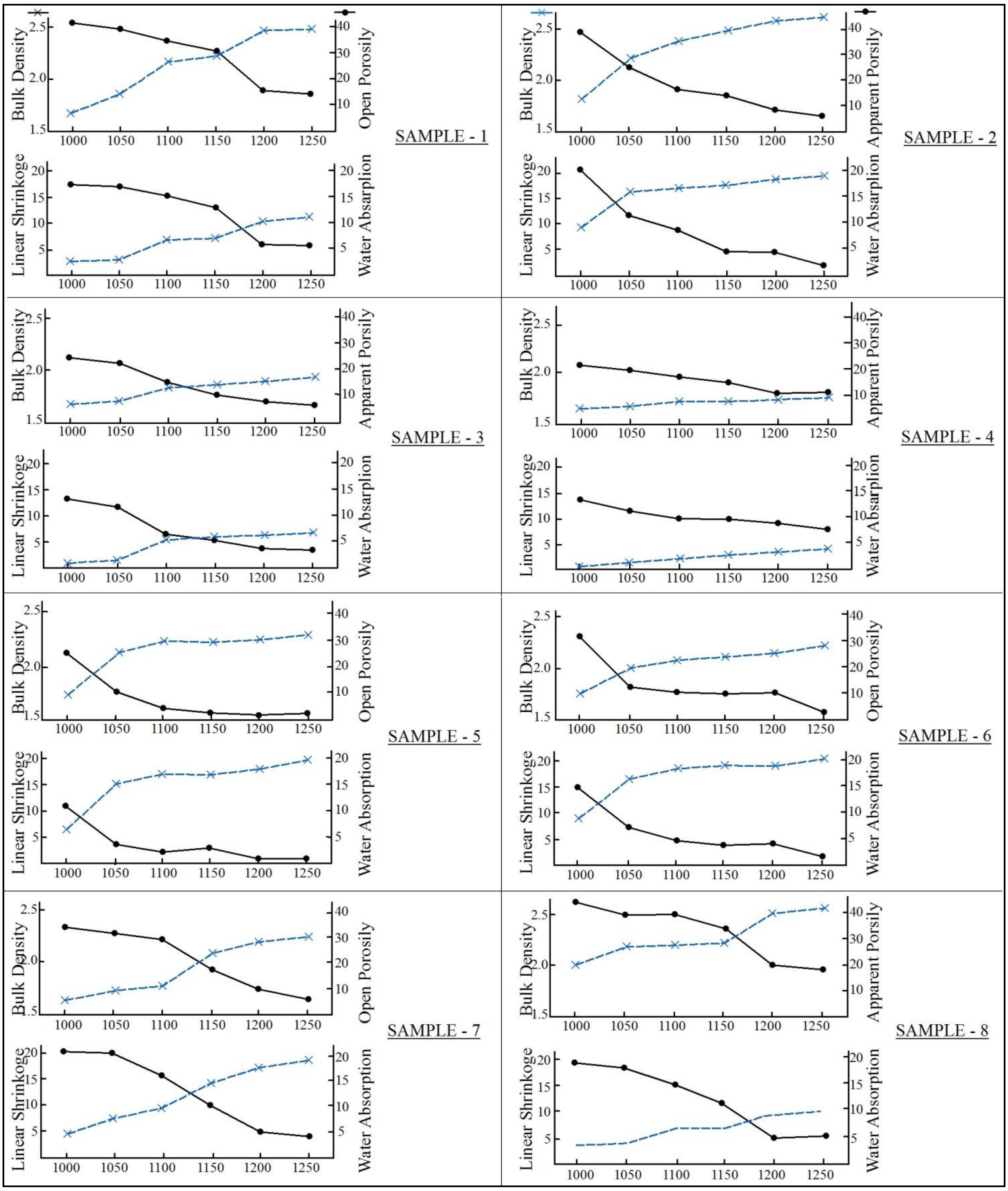


Fig.13: Physical properties of the studied clays after firing
(after Tamar-Agha, 1997)

GRADE

Kaolin clays are classified for industrial purposes into white and coloured depending on the content of iron oxide. The iron content is important in many industries such as paper, white ceramic bodies and white cement. The limit of total iron content ($Fe_2O_3^T$) in the kaolin clay deposits is usually arbitrarily fixed. Zurek and Knapp (1960) considered the upper limit of the iron oxide content in the white kaolin clay as 2%. This content is raised by Yousif and Gabbar (1967) to about 3%. Tamar-Agha (1986) and Tamar-Agha *et al*. (1991) adopted the value 3% of total iron oxide content for the white kaolin clay and justified that for two reasons. The **first** is that the main industry which consumes such clay (mostly plastic and almost similar to the English ball clay) is ceramic industry. Such limit is quite suitable for the majority of ceramic products, apart from white porcelains. The **second** is that the exploration at that stage was raised to categories C_2 and C_1 (Russian norms). The 3% limit of iron oxide content is quite suitable at this level of investigation. This limit can be altered during further exploration stage, taking in account the kind of industry to be consumed in, i.e. eligible to industrial reserves. The presence of organic carbon in the kaolin clay imparts grey shades to the colour. The presence of carbon in such low proportions does not affect most industries, such as ceramics and white cement (because carbon is removed during firing) whereas it is detrimental in other industries such as paper, paint and rubber.

RESOURCES

Prospecting and exploration at the Western Desert of Iraq since the early sixties of the last Century by the Iraq Geological Survey yielded very large mineral resources such as phosphorite, quartz-sand and kaolin clay. The investigations at the Ga'ara Depression resulted in estimating about 960 million tons of white and coloured kaolin clay (categories A, C_1 and C_2). These reserves are summarized in Tables (4 and 5). The investigations at the Hussainiyat locality identified four qualities of kaolin-clay deposits, namely white, coloured black and flint clays. These reserves collectively mounted to about 311 million tons (Mahdi and Al-Hamad, 1990; Mahdi, 1993 and Mustafa *et al*., 1994). Reserves of the coloured kaolin clay are about 300 million tons (Tables 7 and 8) but, in the Northeast Hussainiyat area, white kaolin clay of about 22.5 million tons (Table 6) was outlined (Mahdi and Al-Hamad, 1990). Flint kaolin clay of about 10 million tons (Table 9) was reported by Mustafa *et al*. (1994). The investigations at the Amij locality resulted in estimating about 32 million tons of coloured kaolin clay (category C_1). These reserves are summarized in Table (10) (Mahdi *et al*., 1993).

Table 4: List of deposits, categories of prospecting, reserves and major chemical constituents in the Ga'ara Depression-white kaolin clay deposits (after Tamar-Agha *et al*., 1991)

Name of deposits	Category (Russian norms)	Reserve (million ton)	Chemical analysis (wt.%)				
			Al_2O_3	Fe_2O_3	SiO_2	TiO_2	L.O.I
			%				
Tel Afaif	A + B	0.026	34.0	1.3	52.4	0.1	12.5
	C_1	0.250					
	C_2	4.375					
Wadi Mulusi	A	0.450	19.9	2.6	65.4	–	–
	C_1	1.933	19.5	2.8	64.9	–	–
	C_2	10.515	19.8	2.6	65.4	–	–
Samahat	B	0.018	33.0	1.2	52.3	0.4	–
	C	0.142	26.7	0.9	53.4	0.3	–
Duekhla (U. Horizon)	B	1. 045	32.4	1.48	51.8	1.2	–
	C_1	2.797					
	C_2	1.359					
Duekhla (L. Horizon)	B	3.158	34.3	1.48	49.0	1.1	–
	C_1	3,583					
	C_2	2.577					
Ubairan	C_1	0.580	31.4	1.7	52.2	1.4	11.0
	C_2	18.875	28.3	1.6	53.8	1.5	13.4
South Mlusi (U. Layer)	C_1	170.734	31.4	1.7	52.1	1.4	11.0
	C_2	4.015	30.5	1.3	51.8	1.5	11.9
South Mlusi (L. Layer)	C_2	4.825	26.1	2.0	56.6	1.4	10.3

Continue Table 4:

Name of deposits	Category (Russian norms)	Reserve (million ton)	Chemical analysis (wt.%)				
			Al_2O_3	Fe_2O_3	SiO_2	TiO_2	L.O.I
			%				
East Afaif (First Horizon)	C_2	2.666	30.2	1.6	49.2	1.6	10.9
(Second Horizon)	C_2	2.546	31.6	1.0	51.7	1.9	11.9
(Third Horizon)	C_2	6.595	29.3	1.2	50.6	1.5	10.5
(Fourth Horizon)	C_2	3.462	32.5	1.3	51.5	1.8	11.8
(Fifth Horizon)	C_2	1.340	32.3	1.2	51.6	1.6	11.8
(Sixth Horizon)	C_2	1.931	30.0	1.4	55.7	1.6	10.8
(Seventh Horizon)	C_2	0.992	31.1	0.8	51.4	1.5	11.0
East Tayyarah (Horizon one)	C_2	3.636	29.8	1.1	52.4	1.5	11.1
(Horizon two)	C_2	0.877	31.3	1.1	52.3	1.4	12.4
(Horizon three)	C_2	2.147	32.8	1.1	51.2	1.5	11.8
(Horizon four)	C_2	2.373	30.8	0.9	54.0	1.5	12.1
Al-Sufi	C_1	10.612	24.3	2.5	58.1	1.1	9.0
South Ghadir Al-Sufi	C_2	17.435	24.3	2.3	59.3	1.2	8.4
West Tayyarah	C_1	66.934	30.8	1.9	52.1	1.3	11.2
North Tayyarah	C_2	44.907	27.6	1.8	53.2	1.2	10.2
Wahish	C_2	6.341	21.5	1.8	63.5	1.1	8.0

Table 5: List of deposits, categories of prospecting, reserves and major chemical constituents in the Ga'ara Depression-coloured kaolin clay deposits (after Tamar-Agha *et al*., 1991)

Name of deposits	Category (Russian norms)	Reserve (million ton)	Chemical analysis (wt.%)				
			Al_2O_3	Fe_2O_3	SiO_2	TiO_2	L.O.I
			%				
Tel Afaif	A + B C_1 C_2	0.370 1.075 0.751	32.4	3.7	51.3	0.1	11.8
Wadi Mulusi	A C_1 C_2	1.176 4.481 20.481	21.2 22.3 21.1	6.6 6.2 6.5	59.7 58.8 59.7	– – –	– – –
South Al-Sufi	C_2	205.034	22.0	6.6	57.7	1.2	6.6
East Duekhla	C_2	17.079	25.0	5.0	52.0	1.2	10.2
North Tayyarah	C_2	142.043	23.0	7.0	54.5	1.2	9.4
Wahish	C_2	86.071	22.4	8.7	54.9	1.2	9.2
Wadi Al-Nijili	C_2	95.832	23.6	7.1	54.0	–	–
Telat Al-Humer	REC	34.937	52.2	5.1	55.3	1.04	–

Table 6: List of deposits, categories of prospecting, reserves and major chemical constituents in the Hussainiyat-white kaolin clay (after Mahdi and Al-Hamad, 1990)

Areas within Location 1	Thickness (meter)	Reserve (million ton)	Stripping Ratio	Al_2O_3 (wt.%)	Fe_2O_3 (wt.%)	SiO_2 (wt.%)
Area I	5.1	10.6	3.2	30.3	2.0	51.0
Area II	3.8	5.1	2.9	31.6	2.0	49.6
Area III	7.7	13.0	4.0	28.8	1.7	54.8
Area IV	3.4	3.8	1.7	31.0	2.0	50.6

Table 7: List of deposits, categories of prospecting, reserves and major chemical constituents in the Northeast Hussainiyat-coloured kaolin clay (after Mahdi and Al-Hamad, 1990)

Location Northeast Hussainiyat	Reserve (million ton)	Chemical analysis (wt.%)			
		Al_2O_3	Fe_2O_3	SiO_2	TiO_2
I	191.2	28.7	5.5	50.4	1.3
II	42.1	27.1	5.9	52	1.3

Table 8: List of deposits, categories of prospecting, reserves and major chemical constituents in the Southwest Hussainiyat-coloured clay (after Mahdi *et al*., 1993)

Name of deposits South Hussainiyat	Category (Russian norms)	Reserve (million ton)	Chemical analysis (wt.%)				
			Al_2O_3	Fe_2O_3	SiO_2	TiO_2	L.O.I
Upper layer	C_1	21.5	23.4	10.2	51.5	1.4	9.0
Middle layer	C_1	13.0	21.1	11.7	51.9	1.5	8.7
Lower layer	C_1	16.6	29.2	10.7	44.7	1.5	11.2

Table 9: List of deposits, categories of prospecting, reserves and major chemical constituents in the North Hussainiyat-flint clay (after Mustafa *et al*., 1994)

Location	Reserve (million ton)	Chemical analysis (wt.%)				
		Al_2O_3	Fe_2O_3	SiO_2	TiO_2	L.O.I
North Hussainiyat	15	38.5	1.2	41.5	2.0	14.3

Table 10: List of deposits, categories of prospecting, reserves and major chemical constituents in Amij-coloured kaolin clay (after Mahdi *et al*., 1993)

Location Amij	Reserve (million ton)	Chemical analysis (wt.%)		
		Al_2O_3	Fe_2O_3	SiO_2
A - Upper layer	4.7	24.0	6.2	48.0
A - Lower layer	6.8	29.0	6.0	48.0
B - Upper layer	7.2	24.0	5.5	54.2
B - Lower layer	12.6	29.0	6.8	46.7

TECHNOLOGICAL TESTS

Technological tests on various kaolin clays are carried out by Iraqi authorities, foreign companies, researchers and academicians. The tests are conducted to assess their suitability for various industries such as ceramics, refractories, paper, paints and alumina extraction. Some of these tests are outlined below:

- The first investigation was carried out on Tel Afaif deposit by Zurek and Knapp (1960) during their search for ceramic clay in Iraq. They assessed its suitability for ceramic industry and they believed that wall tiles, utility wares, glazed pipes and other low qualities of fireproof products can be fabricated from the red clay.
- Wadi Mlusi deposit was investigated by Japan Consulting Institute and they recommended its use for glazed clay pipes and utility-ware products (Yousif and Jabbar, 1967).
- Mustaafa (1981) carried out many tests on seven localities at the Ga'ara Depression namely, Duekhla, Tel Afaif, Samhat, Al-Auja, Azzlat Al-Agharri, Bir Mulusi and Chabd Mulusi deposits to assess their suitability for a variety of industrial applications. He concluded that:

  - Clay samples from Samhat, Mulusi and Azzlat Al-Agharri are suitable for the manufacture of paper, paints and plastics. Duekhla and Al-Auja kaolin clays can be calcined first to become suitable for the above end uses.
  - All white kaolin deposits are useful for the manufacture of white cement.
  - Samples from Chabd Mulusi and Duekhla need some processing before use in manufacture of paper, paints, rubber and plastic.
  - All coloured clays are suitable for the manufacture of ceramic and/ or bricks.
  - Fractionation to the required particle size and chemical bleaching can be employed to improve the quality of the clay and upgrade the deposits. Such processes are, for example, necessary to improve the colour properties of the kaolin clay used as filter or coating grade in paper industry.
- Girgis and co-workers (1982) studied samples from Duekhla, Tel-Afaif, Samhat and Bir Mlusi deposits (both white and coloured kaolin clays) for their utilization in ceramic industries and refractories. They concluded that:
  - Physical and refractory properties are comparable in quality to high grade imported kaolin clay.
  - Increase of iron admixtures reduces their refractoriness, improve their sinter ability and affect the colour after firing (from light red to dark brown).
  - White clays are suitable for the manufacture of fireclay refractories of the medium heat duty type. Hard and volume-stable bricks having good technological properties were obtained with proper combination of graded grog and plastic raw kaolin-clay.
  - Engineering bricks, floor tiles, ceramic roofing tiles, building clay bricks and drain pipes could be produced from mixtures of 60% raw coloured clays and 40% grog prepared from the same type of clay and/ or finely ground sand.
- Al-Azzawi and Aly (1983) assessed the suitability of Duekhla kaolin in the manufacturing of electro-porcelain insulators. The raw materials were ground (in porcelain), sieved (through 53 μm mesh) and moulded. The fabricated samples were dried and fired, at rate of 50 °C/30 minutes, to a temperature of 1300 °C with 2 hours soaking time and natural cooling (more than 24 hours). Electrical tests on the fabricated samples showed excellent results in comparison with the imported insulators.
- Al-Sa'adi and Al-Tayyar (1987) used representative sample from Al-Nijili coloured kaolin clay to manufacture chamotte bricks. A mixture of 70% clay and 30% grog (fired at 1420 °C) was moulded using semi-dry method (9% water content) by hydraulic pressure of 500 Kg/cm^2 and fired at 1300, 1350, 1400 and 1450 °C. The fired bricks were then investigated for their physical, mechanical and chemical properties. The results show that such bricks can be produced with optimum firing temperature of 1300 °C and can be used as roofing tiles, ceramic kilns and fire places.
- Hammodi and Abdulla (1987a) extracted alumina from the coloured kaolin clay of Wadi Al-Nijili. The work incorporated two steps, the first to extract impure alumina and the second to purify it to a high grade. The samples were crushed (25 mm), ground (0.6 mm), calcined (at 750 °C for 60 minutes) and leached with 30% sulfuric acid at boiling temperature. The filtrate was evaporated, dried and calcined (at 950 °C for 2 hours) to produce impure alumina. The purification stage involved screening of the impure alumina through 0.85 mm sieve openings then leaching with sodium hydroxide (200 g/l) at a temperature of 200 °C and pressure of 12 bars with stirring. The solution was filtered, carbonated at normal temperature and pressure and filtered. The precipitate (aluminum hydroxide) was then boiled with adequate water, filtered, washed, dried and finally calcined (1200 °C for 1 hour). The purified and calcined alumina had 99.8 wt.% Al_2O_3,

0.080 wt.% Na_2O, 0.027 wt.% Fe_2O_3 and < 0.006 wt.% TiO_2 (Hammodi and Abdulla, 1987a).

- Hammodi and Abdulla (1987b) carried out preliminary tests for the production of alum from coloured kaolin clay. Samples were collected from Duekhla and Tel Afaif, crushed, ground, calcined (at 850 °C for 40 minutes) and treated with dilute sulfuric acid at boiling temperature. The product was treated with an extractant (Primene JMT) diluted in Kerosene in order to remove iron impurity. Alum was successfully produced and its quality seems to fall between Egyptian and Japanese imported alums.
- Mohammed and Putrus (1988) investigated the possibility of raising the brightness of the Duekhla white kaolin clay in order to improve its specifications as filler in the paper industry. The brightness of the Duekhla white kaolin-clay is about 57%, which is below the required specification for its use as filler in the paper industry. Attempts were made to raise its brightness by water washing and chemical bleaching. The brightness was insignificantly raised and further attempts were suggested to remove quartz and iron oxides from the deposit.
- Tamar-Agha (1997) collected nine representative bulk samples from seven localities representing operating mines (Table 1). The samples were characterized for their mineralogical, chemical and physical properties and thermal behavior (shown earlier in the text). He concluded that on the basis of chemical analysis (Table 2) three samples only are suitable for refractories namely, white Duekhla, white Hussainiyat, and Hussainiyat flint-kaolin clays as they are fat and have low total fluxing compounds (alkalies and iron oxides). Addition of pre-calcined kaolin clay (grog) would undoubtedly improve refractoriness. The same samples seem also suitable for the fabrication of sophisticated ceramics such as white ware, porcelain, electroporcelain and chemical sanitary ware, as they fire to slightly off-white colour and sustain high temperatures. The addition of silica sand and fluxing materials are required in order to improve on its making and firing properties such as lowering its plasticity and produce sufficient amount of glassy phase. The Hussainiyat flint-clay is non-plastic and therefore needs a special attention during forming, such as grinding to very fine size or addition of plasticizers for plastic making or semi-dry pressing. Sufi and silty Sufi kaolin clays are suitable for stoneware, beside the above mentioned samples whereas coloured Duekhla, Lower and Upper Hussainiyat and Amij kaolin-clays are suitable for fabrication of red bodies such as roof tiles. Amij kaolin-clay is comparatively impure and is suitable for the fabrication of roof tiles, unglazed pipes and structural bricks (red).
- Plasticity data are plotted on clay workability chart (unpublished data of the British Geological Survey (in Mustafa, 1981) and showed that only silty Sufi and Lower Hussainiyat kaolin clays have the optimum values (Fig.14). White Duekhla, coloured Duekhla, Sufi, Upper Hussainiyat and Amij kaolin clays have moderate shrinkage on drying and thus need to be mixed with non-plastic materials to reduce their plasticity. White Hussainiyat kaolin clay needs addition of plasticizers.
- Al-Haza’a and Tamar-Agha (2004) used Amij kaolin clay and some local raw materials to produce unglazed acid-resistant ceramic tiles which complied with the Iraqi Standard no. 1627 (1991). Fifty six briquettes (8 × 4 × 1 cm) were formed by semi-dry pressing (8% moisture content at 250 kg/cm^2). Fourteen mixes were fired at 1200 °C and another 10 mixes were fired at 1150 °C (soaking time for both batches was two hours). Briquettes fired at 1150 °C did not comply with the Iraqi Standard, whereas those fired at 1200 °C improved vastly and complied with Iraqi Standard. The briquette which showed the

optimum properties (highest modulus of rupture – MOR and compliance with the Iraqi Standard) is composed of 75% Amij kaolin-clay, 15% river sand and 10% cullet.

- Al-Azzawi (2008) prepared glazed porcelain table ware from white Duekhla kaolin clay, Najaf-Karbala feldspar sand, Rutbah quartz sand, limestone or dolomite and cullet. Thirty five mixes were prepared and fired at 1300 °C. The products were tested. Ten samples are considered successful; those were composed of the kaolin clay and the feldspar sand.

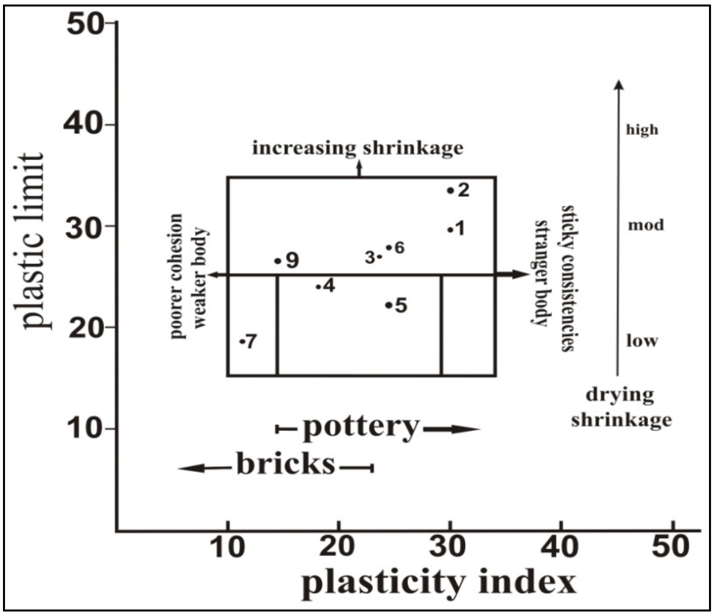


Fig.14: Clay workability chart (Atterberg limit of brick and pottery clays) of the studied clays (after Tamar-Agha, 1997)

CONCLUSIONS

Prospecting and explorations through decades by the Iraq Geological Survey revealed billions of tons of kaolin clay, both coloured and white, at the Ga'ara Depression, Al-Hussainiyat and Amij areas of the Western Desert of Iraq. All investigated clays are of sedimentary origin: the Ga'ara and Hussainiyat kaolin clays are of fluvial, whereas Amij is of paralic origin and Hussainiyat flint clay is associated with karst bauxites. The grade of these kaolin clays is variable; some are of high purity (≥90% kaolinite), whereas others are with variable amount of impurities, such as quartz, iron oxides and organic matter.

Extensive follow-up investigations were carried out on eighteen localities to estimate, verify and categorize the quantity and quality of the kaolin clay deposits. The deposits sought were mostly white kaolin clays ($Al_2O_3 \geq 20\%$ and $Fe_2O_3 < 3\%$) as well as coloured kaolin clays ($Al_2O_3 \geq 20\%$ and $Fe_2O_3 \geq 3\%$). Prospecting and exploration at the Ga'ara Depression resulted in estimating about 960 million tons of white and coloured kaolin clay (categories A, C_1 and C_2), at the Hussainiyat locality about 311 million tons of white and coloured kaolin clays (categories C_1 and C_2), at Amij locality 32 million tons of coloured kaolin clays (category C_2) and at Northeast Hussainiyat locality about 10 million tons of flint kaolin-clay.

RECOMMENDATIONS

Further tests should be carried out on all investigated white kaolin clay deposits in order to assess their suitability for the currently established and future industries such as paper, ceramics, refractories, rubber, paint, pesticides, insecticides, textiles, as catalyst, alum and extraction of alumina. The large resources of kaolin deposits estimated at the Western Desert of Iraq, highly encourages the expansion and development of present industries, which largely depends on this mineral commodity for domestic consumption and/ or for export. The assessment should include the determination of the type of upgrading required for each deposit to meet the specifications needed (such as air-floating, water-washing, etc.) and bagging in order to bring them to the specifications required for local consumption or export.

The use of white Duekhla kaolin clay in wall-tiles industry should be stopped since it does not require high purity and this mineral commodity is by no means cheap. The use of white kaolin clay should be restricted to industries that require such pure clay such as paper, white ware, porcelain, white paint, etc. and flint clay should be used for white cement production instead of white kaolin clay. The overburden and innerburden of the white kaolin clay deposit consist of industrially useful mineral commodities such as dolomite, quartz-sand and coloured kaolin clay; the possibility of their concurrent exploitation reduces the cost of mining of the white kaolin clay.

New industries should be established whereby colored kaolin clay is the major raw materials such as production of alum, alumina, and all types of roof tiles, chemical stoneware, glazed pipes, structural bricks and stoneware. Emphasis should be placed on alumina extraction from kaolin because the kaolin clay in Iraq is the only source of Al-raw material. Experimental results obtained by the Iraq Geological Survey and world industrial experience, in replacing bauxite by kaolin, are promising. Moreover, the bauxite reserves in Iraq are limited with poor quality and difficult mining conditions.

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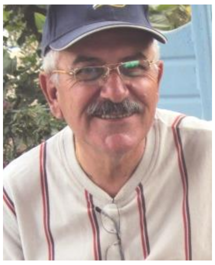
About the author



Dr. Mazin Y. Tamar-Agha, Professor Emeritus at the University of Baghdad, Iraq. He teaches undergraduate and postgraduate courses and supervises postgraduate students in the fields of sedimentary geology and industrial and applied mineralogy. Mazin received his B.Sc. in geology from Mosul University, Iraq (1969) and Ph.D. in Sedimentology from Newcastle University, UK, (1976), where he was a Post-doctoral Research Fellow (1976). He taught in Mosul University (1976 – 1981), and worked in the Iraq Geological Survey (1981 – 1993) and in teaching again at the Baghdad and Salahaddin Universities (1993 to date). He was the Chairman of the Department of Geology in Baghdad University for five years (2000 – 2005). Mazin published about 60 papers in sedimentology, stratigraphy, petroleum geology, mineralogy, geochemistry, industrial and applied mineralogy in Iraqi, regional and international journals.

e-mail: matamaragh@yahoo.com