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The Impact of Diagenetic Constituents on Reservoir Quality of Tahara Sandstones in Gullebi Field, Concession NC7A, Ghadames Basin, NW Libya

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Abstract: *The study area Gullebi Field is located on the southern edge of concession NC7A in the south-central part of the intracratonic Ghadames Basin in northwestern Libya. The Tahara Formation which consists of sandstone and siltstone with shale and iron-rich streaks interbedding is considered the main productive horizon in the study area.*

The stratigraphic framework identified from the analysis and interpretation of the subsurface data for the Late Devonian Tahara Formation, within the Gullebi Field, allow for the recognition of seven (7) lithofacies based on core and wireline-log data which is; (1) dark grey micaceous bioturbated shale (offshore basinal marine environment), (2) parallel laminated silty sandstone and silty shale (deltaic complex environment), (3) varicolored silty shale and bioturbated iron-rich shale (lagoonal to river influences environment), (4) bioturbated sand and shale (beach environment), (5) interlaminated shale and silty sandstone (coastal plain environment), (6) massive sandstone and gravel (fluvial; river channel environment), (7) rippled and fossiliferous sandstone (deltaic-beach environment).

The Tahara sandstones can be classified as quartzarenites and sublitharenite in terms of their modal composition. Quartz grains constitute of an average about (86%) of the total sand grains, sparse feldspar grains account for about (2%) and rock fragments of an average (11%). Two types of porosity are recognized in the Tahara sandstones: (1) primary intergranular porosity (2) secondary porosity; dissolution of unstable grains was the dominant process to create secondary porosity.

The diagenetic processes and their products may be identified to shed light on the sandstone quality variation of the Tahara Formation. A composite paragenetic sequence explaining diagenetic events through time for the Tahara sandstone of Gullebi Field can be proposed.

Based on petrography data, identified diagenetic constituents, and proposed paragenetic sequence, three (3) possible reservoir quality types or associations can be identified for the Tahara sandstones in the Gullebi Field which are:

1- Good quality type of the Tahara sandstone was found to be associated with beach and deltaic complex lithofacies.

2- Medium quality type of the Tahara sandstone was found to be associated with fluvial channellithofacies.

3- Poor quality type of the Tahara sandstone was found to be associated with the lagoonal, coastal plain, and offshore marine lithofacies.

The use of a diagenetic sequence integrated with depositional lithofacies represents an initial step in predicting regions of maximum enhanced and preserved porosity on the assessment of reservoir quality in the Tahara sandstones of the Gullebi Field.

Keywords: *Diagenesis, Tahara Sandstones, Gullebi Field, Ghadames Basin, Reservoir Quality.*

1. INTRODUCTION

The Hamada (Ghadames) Basin is one of the major petroleum provinces in Libya, where the sandstone reservoirs of the Paleozoic rocks represent the main target for oil exploration. In 1955 and after the discovery of the large Edjeleh Field in Algeria by French company on the very boundary of the Esso concession 1, all the basins were considered as a frontier areas and many concessions were awarded in Libya. In 1957 Esso began operations in concession 1 close to the recent French discoveries in Algeria. Their second well made a gas discovery which, on appraisal, turned out to be a significant find containing both oil and gas in multiple reservoirs [1]. Several discoveries were made in the following years including BirTlacsin (1959), Tiji (1960) and A-NC118 (1985) to the north, and Z-66 (1961) in the central area, Al Hamra Field complex (1959-1962), A-NC40 (1979) and A-NC40B (1981) to the southeast, along with Al Wafa field, D1-52 (1964) and A-NC175 (1997) to the southwest (Elruemi, 2003) [2].

The Gullebi Field (also known as Gazeil Field) was discovered in 1960 by the Oasis Oil Company which was the operator of the concession 26 (NC7A, in present time) by stroke oil and gas in the exploration well A1-26, producing from Tahara horizon. A second well, drilled 16 Km to south-southeast found Devonian reservoir water bearing and was abandoned. Oasis then stepped out 17 Km to northeast of A1-26 well and found gas in the Tahara, AouinetOuenine 'A' and OuanKasa formations at A3-26, and gas in the Tahara and AouinetOuenine 'A' in A4-26. Finally, Oasis offset the discovery well with A5-26 which found gas over oil in the Tahara and oil in the AouinetOuenine 'A' Formation (AGOCO, 1997) [3].

The National Oil Company (NOC) conducted an extensive drilling program at Gullebi Field from 1975 to 1977, where a total of 11 wells have been drilled. In 1988, N.O.C drilled the HH1-NC7A 8Km to north of A13-NC7A and found gas over water in Tahara Formation (AGOCO, 1997)[3]. Laterthe concession was awarded to the Arabian Gulf Oil Company (AGOCO), which has continued exploration and development activities in this area. In concession NC7A, many oil fields were discovered and boreholes were drilled with proven reserves of oil and gas, they have never been brought into production.

The most considerable oil accumulations in Ghadames Basin are in the licensed NC7A and NC8A represented by Gullebi-Kebir and El Hamra Fields

2. LOCATION OF THE STUDY AREA

The study area Gullebi Field is located in the south central part of Ghadames Basin, where it occupies the southern part of the concession NC7A, between latitudes 29°30 N to 30º00 N and longitudes 11°30E to 11º87E (Fig. 1). The Gullebi Field has a trend of northeast-southwest over a total length of 48 km and a width of 5 km (AGOCO, 1997) [3].

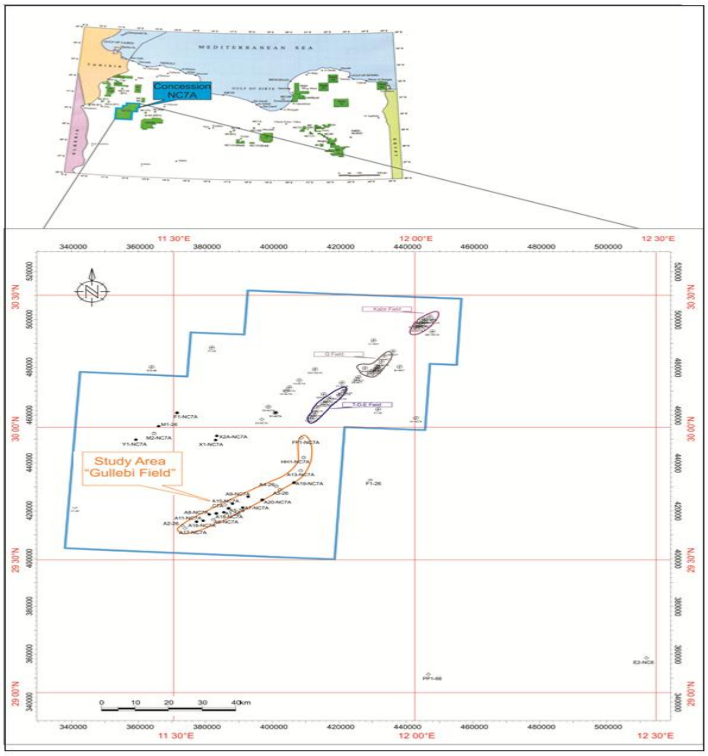


Figure1. *Location Map of the study area (Gullebi Field, Concession NC7A)*

3. PREVIOUS WORK

The first studies in Libya and in the Hamada (Ghadames) Basin specific have been conducted by the Italian geologist during the occupation time 1901-1940. After the first oil discovery in West Libya in m-1950s, the exploration activity has accelerated by many oil companies and many boreholes have been drilled. Since that time the subsurface studies and researches of the Hamada (Ghadames Basin) were increased. . Beicip (1972-1973) [4] made a series of studies about Ghadames Basin including field trips and reports, palynological, geochemical and economic studies. The Paleozoic rocks were the main focus for most of these studies for their petroleum importance in the basin including. Regarding the Tahara Formation, a study was conducted by Ali (1977) [5], sedimentological study of the Tahara Formation (Gullebi Area-NC7A) in which he examined a total of 485 feet of core samples cut in different parts of Tahara Formation in four wells (A11-NC7A, A8-NC7A, A12-NC7A, A6-NC7A) drilled in Gullebi Field. The study showed that the Tahara deposits in the studied wells exhibit fluviatile to fluvio marine deltaic environment. Bellini and Massa (1980) [6] made study about the stratigraphic contribution to the Palaeozoic of the southern basin of Libya , where the general framework of Ghadames Basin had been discussed. Bellini and Massa (1980) [6] made study about the stratigraphic contribution to the Palaeozoic of the southern basin of Libya , where the general framework of Ghadames Basin had been discussed. Echikh and Suleiman (1982) [7] conducted a preliminary geological study and petroleum evaluation of Ghadames Basin, Libya. Bracaccia et al., (1991) [8] studied the sedimentology of the Silurian-Devonian series in the southeastern part of the Ghadames Basin. Regional study of Ghadames Basin “analysis and evaluation” conducted by Maria (1991) [9], where Ghadames Basin has been studied in details from regional tectonic evolution to the petroleum geology, this study classified as internal report in Arabian Gulf Oil Company. El-Rweimi (1991) [10] studied the geology of the Aouinet Ouenine and Tahara Formations, Al Hamada Al Hamara Area, Ghadames Basin. A study was conducted by Hassi (1993) [11] as a part of MSc. thesis “dynamic stratigraphy of the Tahara Formation, Hamada Basin, Western Libya”, Hassi studied a number of three wells (A8-NC7A, A12-NC7A, A13-NC7A) within Gullebi Field and concluded that the Tahara Formation is a storm dominated siliciclastic shelf shoreface sequence deposited on the eastern margin of the intracratonic Hamada Basin. Where the series of studied wells is thought to have been oriented at an angle to the shoreline and are thought to reflect a transition to an increasingly offshore distal position. Shah et al., (1993) [12] discussed the effects of synsedimentary processes on porosity within the Palaeozoic sandstone reservoirs of the Hamada Basin, NW Libya. Many other studies had been conducted on Ghadames Basin, in various geological sections.

The Palaeozoic and Mesozoic stratigraphy of eastern Ghadames and Western Sirt Basins were investigated by Belhaj (1996) [13]. The Arabian Gulf Oil Company (AGOCO) has conducted an exploitation evaluation study in the Gullebi Field (AGOCO,1997) [2] containing some cross-sections and maps for the Paleozoic reservoirs including Tahara Formation. Echikh (1998) [14] discussed the geology and hydrocarbon occurrences in the Ghadames Basin within Algeria, Tunisia and Libya.Boote et al., (1998) [15] discussed the Palaeozoic petroleum systems of North Africa.

Elfigih (2000) [16] conducted a study as a part of PhD thesis about regional diagenesis and its relation to facies change in the Upper Silurian, Lower Acacus Formation, Hamada (Ghadames) Basin, North Western Libya. El-Mehdawi (2000) [17] studied the palynology of the Upper Tahara Formation in concession NC7A, Ghadames Basin. Hallet (2002) [1] finished a book about petroleum geology of Libya, where all depositional basins in Libya had been discussed in details. Abugares (2003) [18] studied the petroleum geology of the Palaeozoicclastics of the Murzuq Baisn, Al Atshan saddle and the southern part of the Ghadames Basin, Libya. Arduini et al., (2003) [19] studied the Silurian-Devonian sedimentary geology of the Libyan Ghadames Basin. Some other studies have been conducted on the level of Tahara Formation in some other local areas including, Burki and Turner (2003) [20] discussed the hydrocarbon reservoir potential of the Tahara Sandstones, Ghadames Basin, Western Libya.

Ghori and Mohammed (2003) [21] made a petroleum system modelling study in Ghadames Basin. Sikander (2003) [22] made a study about structural development, geology and hydrocarbon potential of the Ghadames and Murzuq Basins, another study by Sikander et al., (2003) [23], where the geochemical source-maturation and volumetric evaluation of Lower Palaeozoic source rocks in the West Libyan Basins have been studied.

Elruemi W. (2003) [24] discussed the geologic evolution of Ghadames Basin-impact on hydrocarbon prospectivity, with cross sections and some maps, in addition of thins sections analysis.

Underdown et al., (2007) [25] made a study about the importance of constraining regional exhumation in basin modeling where the hydrocarbon maturation history of the Ghadames Basin, North Africa has been discussed.

To date the impact of diagenetic processes on reservoir quality of Tahara sandstones in Gullebi Field remain unknown, so in this paper we will try to address these processes and their effects on the reservoir quality variation.

4. TECTONIC AND STRATIGRAPHY OF THE GHADAMES BASIN

The Ghadames Basin is situated in north-western Libya, and extends into southern Tunisia and eastern Algeria. The basin is bounded structurally and topographically by the Nefusa Uplift to the north, the Tripoli-Assuda Arch in the east the Gargaf Uplift in the south, and the northern extension of the Thempoka Arch in the west (Fig. 2). The Ghadames Basin classified as an intracratonic sag basin, containing a mainly clastic sedimentary section more than 15000 feet thick, where the Paleozoic section is unconformably overlain by Mesozoic and Tertiary strata [26].

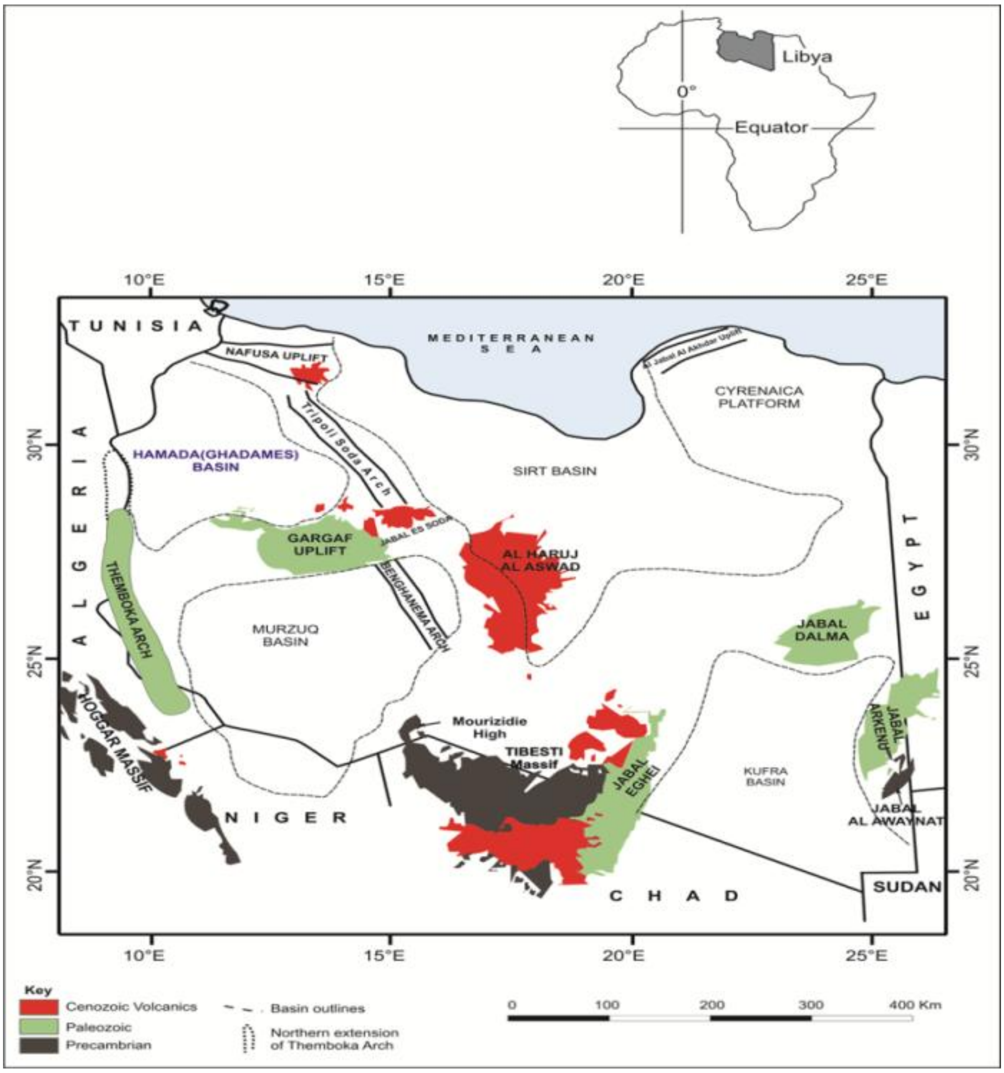
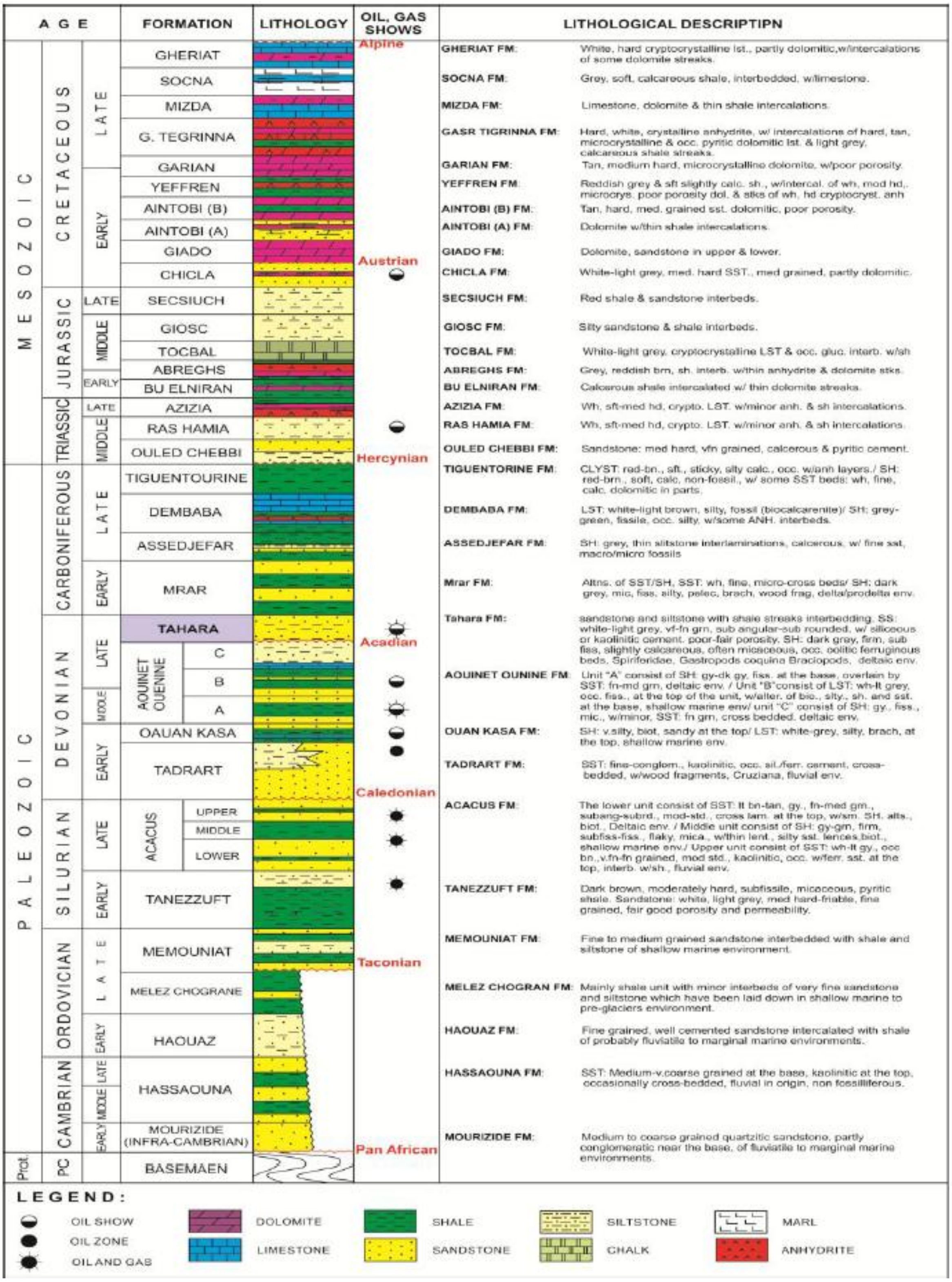


Figure2. *Ghadames Basin, regional boundaries and tectonic element of Libya, (modified after [27] and [16].*

The sedimentary record of the Ghadames cratonic basin and nearby regions from Early Cambrian to Late Paleozoic is divided by five major unconformities (Figs. 3, 4). These unconformities divide the cratonic stratigraphic column into four intra-cratonic sequences (Caledonian—Hercynian tectonic cycles). The sequences are major rock-stratigraphic units (sedimentary cycles) which can be identified where preserved [9] (unpublished AGOCO report). The timing of the unconformities represented are:

(1) Late Carboniferous-Early Permian (HercynianUnc.).
(2) Late Devonian-Early Carboniferous (Acadian Unc.)
(3) Late Silurian-Early Devonian (Caledonian Unc.)
(4) Late Ordovician (TaconianUnc.)

(5) Early Cambrian (Pan African Unc.)



GHERIAT FM:	White, hard cryptocrystalline lst., partly dolomitic,w/intercalations of some dolomite streaks.
SOCNA FM:	Grey, soft, calcareous shale, interbedded, w/limestone.
MIZDA FM:	Limestone, dolomite & thin shale intercalations.
GASR TIGRINNA FM:	Hard, white, crystalline anhydrite, w/ intercalations of hard, tan, microcrystalline & occ. pyritic dolomitic lst. & light grey, calcareous shale streaks.
GARIAN FM:	Tan, medium hard, microcrystalline dolomite, w/poor porosity.
YEFFREN FM:	Reddish grey & sft slightly calc. sh., w/intercal. of wh, mod hd,. microcrys. poor porosity dol. & stks of wh, hd cryptocryst. anh
AINTOBI (B) FM:	Tan, hard, med. grained sst. dolomitic, poor porosity.
AINTOBI (A) FM:	Dolomite w/thin shale intercalations.
GIADO FM:	Dolomite, sandstone in upper & lower.
CHICLA FM:	White-light grey, med. hard SST., med grained, partly dolomitic.
SECSIUCH FM:	Red shale & sandstone interbeds.
GIOSC FM:	Silty sandstone & shale interbeds.
TOCBAL FM:	White-light grey, cryptocrystalline LST & occ. gluc. interb. w/sh
ABREGHS FM:	Grey, reddish brn, sh. interb. w/thin anhydrite & dolomite stks.
BU ELNIRAN FM:	Calcerous shale intercalated w/ thin dolomite streaks.
AZIZIA FM:	Wh, sft-med hd, crypto. LST. w/minor anh. & sh intercalations.
RAS HAMIA FM:	Wh, sft-med hd, crypto. LST. w/minor anh. & sh intercalations.
OULED CHEBBI FM:	Sandstone: med hard, vfn grained, calcerous & pyritic cement.
TIGUENTORINE FM:	CLYST: red-bn., sft., sticky, silty calc., occ. w/anh layers./ SH: red-brn., soft, calc, non-fossil., w/ some SST beds: wh, fine, calc. dolomitic in parts.
DEMBABA FM:	LST: white-light brown, silty, fossil (biocalcarenite)/ SH: grey-green, fissile, occ. silty, w/some ANH. interbeds.
ASSEDJEFAR FM:	SH: grey, thin siltstone interlaminations, calcerous, w/ fine sst, macro/micro fossils
Mrar FM:	Altns. of SST/SH, SST: wh, fine, micro-cross beds/ SH: dark grey, mic, fiss, silty, pelec, brach, wood frag, delta/prodelta env.
Tahara FM:	sandstone and siltstone with shale streaks interbedding. SS: white-light grey, vf-fn grn, sub angular-sub rounded, w/ siliceous or kaolinitic cement. poor-fair porosity. SH: dark grey, firm, sub fiss, slightly calcareous, often micaceous, occ. oolitic ferruginous beds, Spiriferidae, Gastropods coquina Braciopods, deltaic env.
AOUINET OUNINE FM:	Unit "A" consist of SH: gy-dk gy, fiss. at the base, overlain by SST: fn-md grn, deltaic env. / Unit "B"consist of LST: wh-lt grey, occ. fiss., at the top of the unit, w/alter. of bio., slty., sh. and sst. at the base, shallow marine env/ unit "C" consist of SH: gy., fiss., mic., w/minor, SST: fn grn, cross bedded. deltaic env.
OUAN KASA FM:	SH: v.silty, biot, sandy at the top/ LST: white-grey, silty, brach, at the top, shallow marine env.
TADRART FM:	SST: fine-conglom., kaolinitic, occ. sil./ferr. cement, cross-bedded, w/wood fragments, Cruziana, fluvial env.
ACACUS FM:	The lower unit consist of SST: lt bn-tan, gy., fn-med grn., subang-subrd., mod-std., cross lam. at the top, w/sm. SH. slts., biot., Deltaic env. / Middle unit consist of SH: gy-grn, firm, subfiss-fiss., flaky, mica., w/thin lent., silty sst. lences,biot., shallow marine env./ Upper unit consist of SST: wh-lt gy., occ bn.,v.fn-fn grained, mod std., kaolinitic, occ. w/ferr. sst. at the top, interb. w/sh., fluvial env.
TANEZZUFT FM:	Dark brown, moderately hard, subfissile, micaceous, pyritic shale. Sandstone: white, light grey, med hard-friable, fine grained, fair good porosity and permeability.
MEMOUNIAT FM:	Fine to medium grained sandstone interbedded with shale and siltstone of shallow marine environment.
MELEZ CHOGRAN FM:	Mainly shale unit with minor interbeds of very fine sandstone and siltstone which have been laid down in shallow marine to pre-glaciers environment.
HAOUAZ FM:	Fine grained, well cemented sandstone intercalated with shale of probably fluviatile to marginal marine environments.
HASSAOUNA FM:	SST: Medium-v.coarse grained at the base, kaolinitic at the top, occasionally cross-bedded, fluvial in origin, non fossilliferous.
MOURIZIDE FM:	Medium to coarse grained quartzitic sandstone, partly conglomeratic near the base, of fluviatile to marginal marine environments.

Figure3. *Lithostratigraphic chart of Hamada (Ghadames) Basin, Libya.modified after [28].*

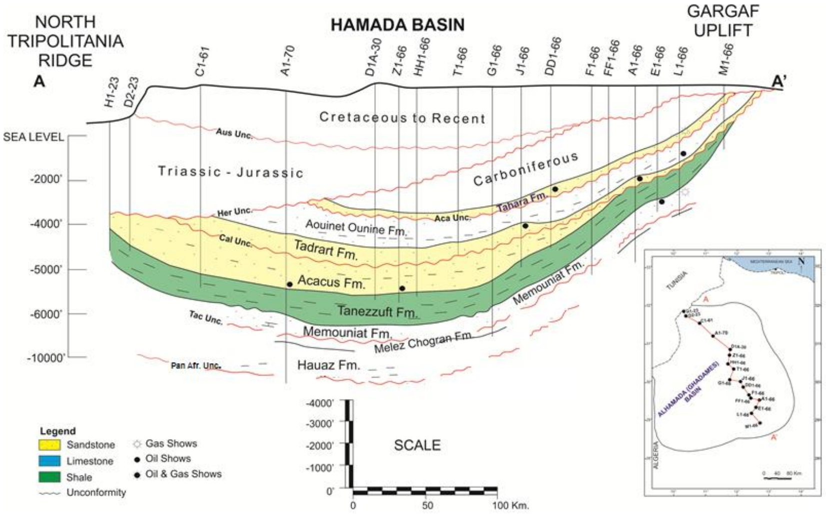


Figure4. *Regional NW-SE structure cross section in Hamada(Ghadames Basin) [29], [30].*

4.1. Precambrian

During the Precambrian, numerous continents, cratonic fragments and island arcs were collided during the so called Pan African Orogeny to give birth to the southern megacontinent of Gondwana. Two large cratonic blocks dominated the North Africa: The West African Craton and the East Saharan Craton. When these two cratons collided together, a large Pan African collisional zone developed between them “the Trans-Saharan Megabelt”. As a result the Precambrian basement comes to surface in several places around the Murzuq and Kufra Basins, represented in Hoggar Massif in neighboring Algeria, Tibesti Massif with border of Chad and Jabel Al Awaynat eastern Kufra Basin.

The Precambrian rocks in Libya consist of a wide range of highly folded metamorphic and predominantly igneous rocks which form part of the North Africa Craton. Towards the end of the Pan-African orogeny, Libya was located on the passive margin of West Gondwana. The final phase of the Pan-African orogeny in the Early Cambrian produced a series of north-south to northwest-southeast uplifts and troughs which controlled sedimentation in the early Paleozoic (Fig. 5).

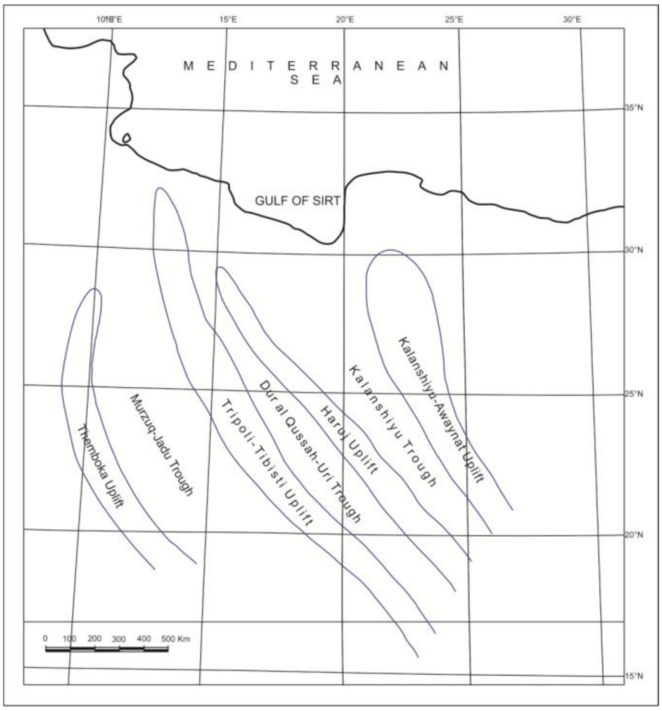


Figure5. *Paleogeographic maps of Libya, showing Pan-African structures that formed during late Precambrian to Late Carboniferous tectonism [31].*

4.2. Paleozoic

The sedimentation during the Cambrian period was controlled by the mature relief and tectonically stable platform, which was inundated by very shallow seas [32]. The first Cambrian filling of the Ghadames Basin were the continental sandstone (Mourizidie Formation), which resting unconformably on the metamorphic basement and overlain by the Late Cambrian (HassaunaSandtone) Formation that representing the first cycle of the Gargaf Group.

By the Ordovician age, the eustatic sea level were raised, but apart from that, the sandstone deposition were still dominated and the deposition of the Early Ordovician (Hawaz Formation) has took place. This last one was unconformably overlain by the transgressive marine shales (MelezChograne Formation). The general tectonic stability of the shelf across North Africa through this period resulted in the deposition of broadly similar Cambrian and Ordovician successions across the entire region.

During the Late Ordovician Western Gondwana was located near the south pole, and the areas of North African and Arabian shelf were covered by a thick ice sheet. At the beginning of the Ashgillian stage, an uplift of the area occurred corresponding to the Taconiantectonic, the subsequent erosional activity by the ice cover determined the creation of a series of large and long troughs, which were later filled by fluvioglacial and glacio-marine deposits of Memouniat Formation [33].

After the peak of the late Ordovician glaciation during the Hirnantian , ice melting led to a rapid eustatic sea-level rise and a far-reaching southward transgression, announcing the beginning of the Silurian period (Fig. 6). The thick shales of Tanezzuft Formation were deposited in this time, and it is basal part the “hot” black, radioactive, graptolitic shales, represented the major source rocks for the Palaeozoic oil accumulations of North Africa.

Sediments source area, uplifted due to epeirogenic movement in the Middle to Late Silurian time, the coast line began to shift seawards and numerous rivers transported enormous amounts of sand from the Gondwanan hinterland towards the North African coast, resulted in deposition of the sand rich Acacus Formation, it is basal member constitute the most important reservoirs of the (Hamada) Ghadames Basin.

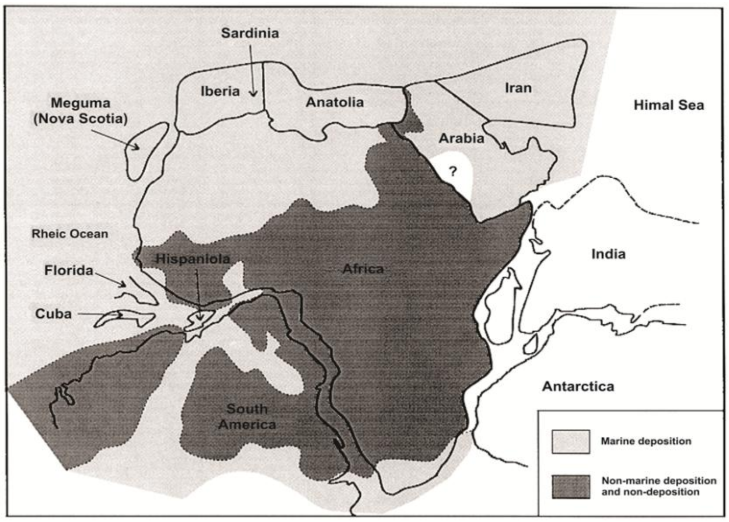


Figure6. *Early Silurianpalaeo geographic map of Gondwana [34].*

During the Late Silurian –Early Devonian the Caledonian Orogeny initiated from the collision between West Africa and North America, caused uplifting and erosion of the southwestern and southern flank of the Ghadames Basin, the continental Lower Devonian (Tadrart Formation) deposits had took place, and it is seen to directly overly the Upper Silurian (basal Acacus) [14].The subsequent Devonian succession includes the transgressive shallow marine sands of the OuanKasaFm, and the Aouinet-Ouenine Fm.

The basin was gently uplifted during Late Devonian time corresponding to the Acadian Orogeny [13]. The termination of the Devonian period in the Ghadames Basin is marked by a return to dominantly regressive conditions with the deposition of the sands of the Tahara formation.

During the Carboniferous several strata generally include mixed lithologies of shale, siltstone, sandstone and limestone were deposited in the basin (Mrar,Assedjefar, Dembaba and Tiguentourine formations), in other words, the period characterized by Monotonous eustatic sea-level oscillations, sands and shales deposition, and only during rare occasions, the siliciclastics replaced with carbonates.

The Hercynian orogeny (Collision between Gondwana and Laurasia) (Fig. 7), considered the most conspicuous feature of the basin. During this phase all the Northern flank of Ghadames basin was uplifted and eroded from Cambrian-Ordovician to Devonian (Fig. 4), and overlain by a Mesozoic basin (the Hamadah Basin in Libya) with spectacular angular unconformity and markedly different basin configuration to that of the Palaeozoic[1].

After the Hercynian orogeny reached its culmination in the late Carboniferous, much of the North African margin was uplifted and deformed. Continental conditions were established, extensive erosion took place, and the North African platform was deformed into a series of swells and sags extending from Morocco to western Egypt [1]. In Libya, the Nafusah Uplift, Al Qarqaf Arch (Separated Ghadames Basin from Murzuq Basin), Sirt Arch, Ennedi-Al Awaynat Uplift and their associated troughs were formed (Fig. 8).

4.3. Mesozoic

During the early Mesozoic, extensional movements caused by the opening of the Tethys and Atlantic oceans developed a cratonic sag basin (Known as the Hamada Basin in Libya and Triassic Basin in Algeria), the whole basin was tilted toward the north, the depocenter of the basin was migrated north than during the Paleozoic, thus a significant space has been generated for the deposition of clastic, and evaporite sections unconformably overlies the Paleozoic basin, followed subsequently by carbonate deposition occurred throughout the remainder of the Mesozoic over much of central North Africa.

The widespread deltaic regression system dominated in the Lower Cretaceous was terminated by the Austrian Orogeny. Transpressional wrenching and uplift occurred along pre-existing Paleozoic and Pan African crustal heterogeneities with locally intense faulting and uplift, as experienced on the Themboka Arch [15].

During the Latest Cretaceous-Eocene time the Alpine Orogeny event, caused by collision of Africa-Arabia and Eurasia affect Ghadames basin, the exhumation related to this tectonic event increases in intensity eastwards across the Ghadames Basin, being greatest over the uplifted basin margins to the south (Gargaf and Themboka arches) and east (Nafusah Uplift) [25].The compressional tectonic movements during this phase tilted the Triassic Basin to its present configuration. Also the tectonic conditions changed from passive to an active margin over the entire North African region. In general, the deeply seated high-angle normal faults had undergone major Cambro-Ordovician activity and were subsequently reactivated during the Alpine compression. The Alpine Orogeny marked the last major geodynamic event to affect Ghadames Basin and it had a great impact on the details of the final structural architecture of the basin [24].

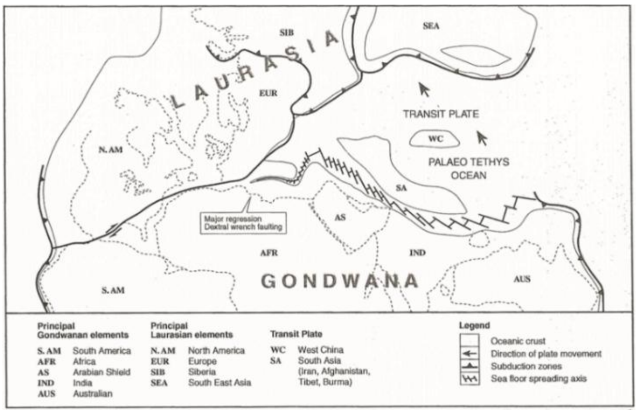


Figure7. *Hercynian compression as result of Late Carboniferous plate collision between Laurasia and Gondwana [1].*

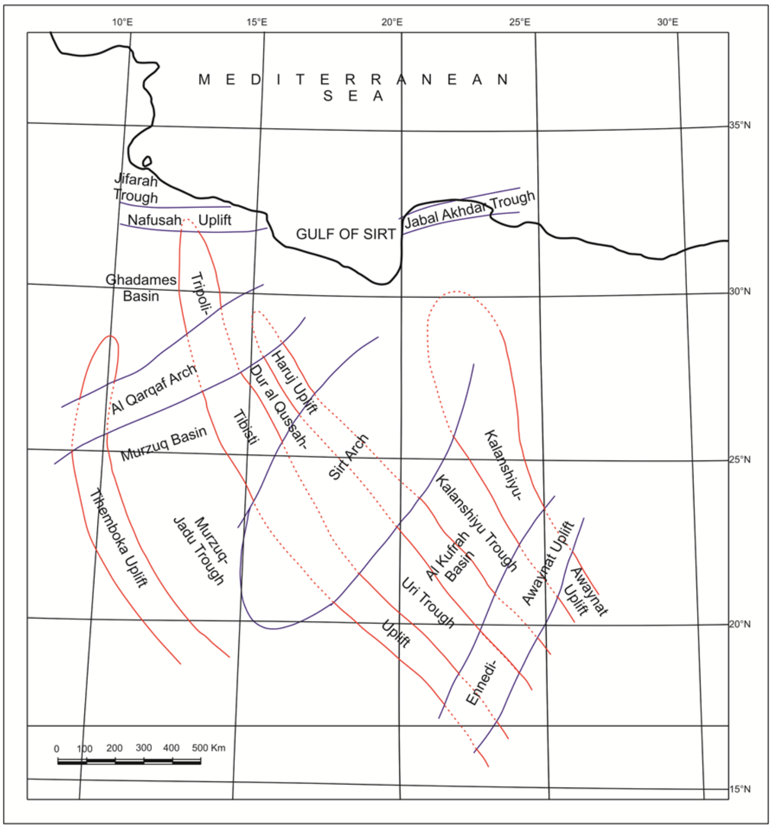


Figure8. *Paleogeographic maps of Libya, showing Hercynian structural trends caused by the Late Carboniferous collision between Gondwana and Laurasia.[31].*

5. METHODOLOGY

lithofacies have been recognized in the Tahara Formation by using core samples and wireline logs of 7 studied wells(Table 1) [35].Petrographic study of selected 26 thin-sections in 6 wells have been conducted to examine the mineralogic composition, texture, porosity types and diagenetic events or characteristics of the Tahara Formation. The thin sections were prepared with blue epoxy-impregnated samples. Total mineral composition was determined by point counting of 300 grains per thin section using the Gazzi-Dickinson quantification method [36] and the description scheme of [37]. Modal analysis for the examined thin sections of Tahara Formation was also conducted.Porosity and permeability data were obtained through a combination of visual estimates from thin sections impregnated with blue resin, and porosity and permeametry measurements of one- inch diameter plugs taken from samples. Information from the field and laboratory was then combined to construct lithofacies descriptions, a diagenetic evaluation, and a description of reservoir quality.

Table1. *List of studied wells (See Fig. 1 for wells location).*

Well Name	Well Status	K.B (ft)	GL (ft)
F1-26	Suspended & Gas	2102	2043
M1-26	Oil	1993	1933
A8-NC7A	Oil	2114	2061
A9-NC7A	Dry	2099	2046
A12-NC7A	Dry	2086	2046
A13-NC7A	Minor Gas	2087	2036
X1-NC7A	Oil	2033	2016

6. LITHOFACIES

Based on continuous cores and electrical log data (mainly GR. Log) from seven selected wells namely; (A8-NC7A, A9-NC7A, A12-NC7A, A13-NC7A, X1-NC7A, M1-26, F1-26)(Fig. 9), seven lithofacies have been recognized in the Tahara Formation. Each lithofacies is defined on the basis of lithology, fossil contents and sedimentary structures. For detailed lithofacies description see (Elfigih O. B. and BalmshkanS. R., 2018, In IJETAE, Vol. 8, Iss. 6)[35]. The used identified lithofacies are as following:

(1) Dark grey micaceous bioturbated shale (offshore basinal marine environment).

(2) Parallel laminated silty sandstone and silty shale (deltaic complex environment).

(3) Varicolored silty shale and bioturbated iron-rich shale (lagoonal to river influences environment).

(4) Bioturbated sand and shale (beach environment).

(5) Interlaminated shale and silty sandstone (coastal plain environment).

(6) Massive sandstone and gravel (fluvial; river channel environment).

(7) Rippled and fossiliferous sandstone (deltaic-beach environment).

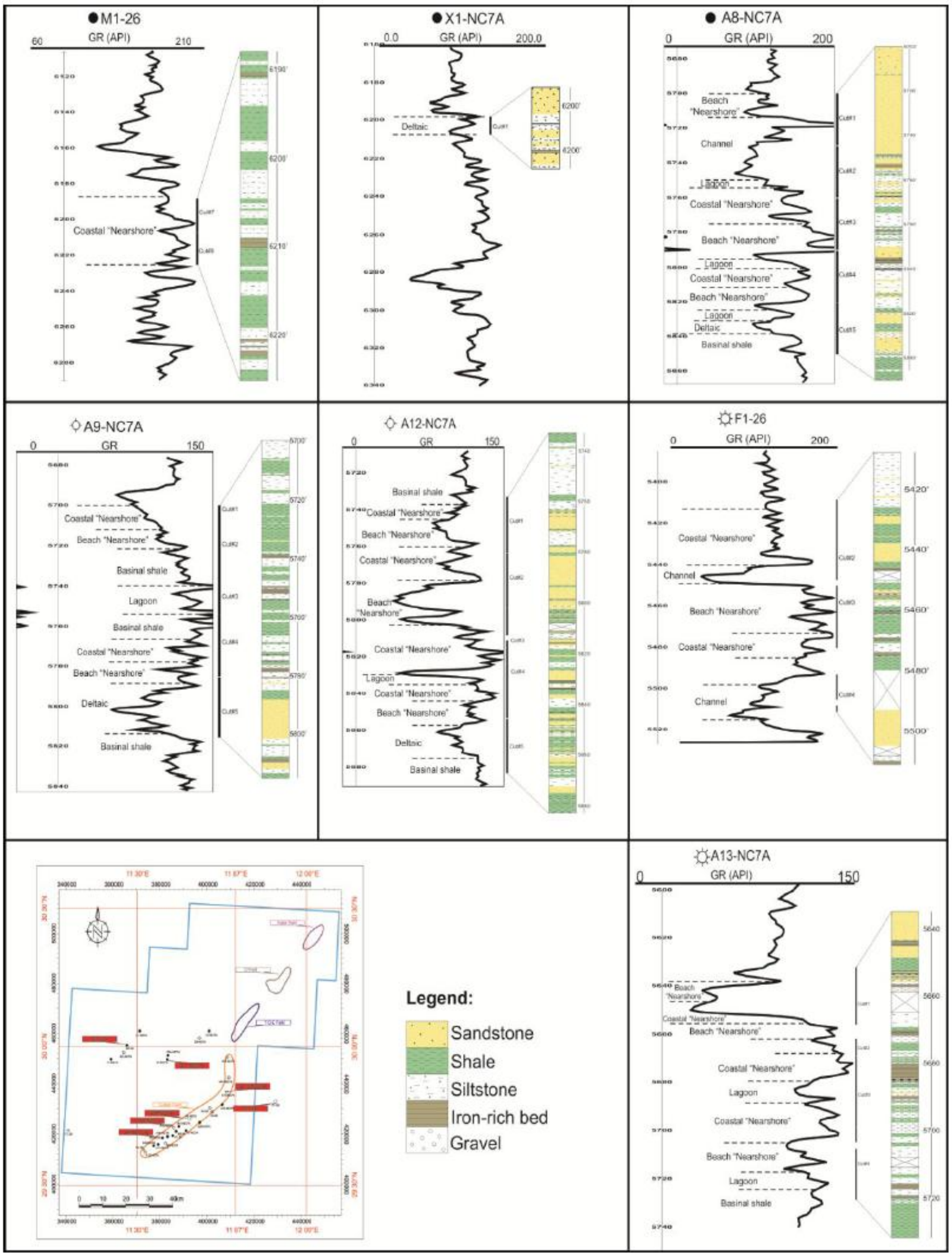


Figure9. *Gamma Ray (GR) log response of the studied seven (7) wells, showing the cored interval and the different lithofacies of Tahara Formation, ConcessionNC7A [37].*

7. PETROGRAPHY

7.1. Quartz

Monocrystalline quartz grains are the most common in the studied thin sections of Tahara Formation, ranging from 45% to 98%. The characteristic quartz grain size is ranging from 0.0625 mm to 0.125

mm (very fine to fine grain) for most of the sand units and it is increased locally for some units to 0.5 mm (medium grain), mostly well sorted, subangular – subrounded, and dominantly smoky white in color occasionally show anomalous birefringence may be due to the thin section being thicker than 30 µm (Fig. 10; I & II). Most of the quartz grains are characterized by straight contact (grain supported). Quartz grains are intensively fractured may be of tectonic origin.

7.2. Feldspar

Feldspar grains are of minor constituent in the studied thin sections of Tahara Formation, varies from 0.3% up to 8%, Orthoclase (potassium feldspar) is the only feldspar present, occurs as angular to sub angular detrital grains (Fig. 10; I & II), and it is commonly dissolved and replaced by some clay minerals.

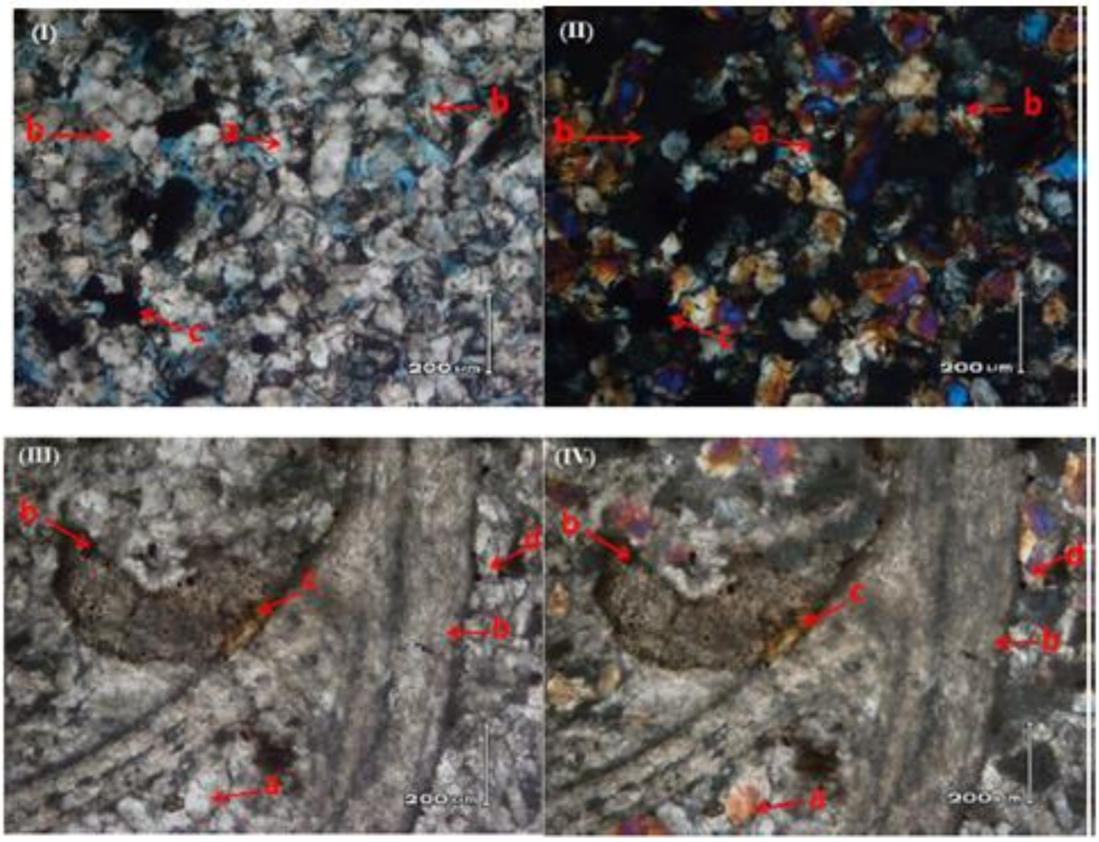
7.3. Rock Fragments

Rock fragments represent the second dominant detrital composition which ranging from 0% to 54% averaging 11% of the total examined detrital constituents. They are represented by clay clasts composed mainly of finely crystalline clay minerals between quartz grains found mostly in all thin sections. Some Brachipods and Pelecypods fragments were found to be associated with rippled and fossiliferous sandstone lithofacies in A8-NC7A and A12-NC7A wells (Fig. 10; III - VI).

7.4. Accessory Minerals

The most common accessory minerals associated with the Tahara sandsare the opaque minerals (organicmaterials), which were found in most thin sections with variety amounts ranges from trace to 3.3%.The mica in Tahara Formation found as trace or up to 2% locally. Predominately mica muscovite was present, which occurs as elongated flakes, easily identified by its parallel extinction and of platy nature, colorless in (PPL) and shows bright second-order color under (XPL). Occasionally appeared to be bent between rigid quartz grains (Fig. 10; VII & VIII).

Detrital Glauconite exist locally up to 18%, and recognized by its green color under both (PPL and XPL) (Fig. 10; IX & X). Chamosite (iron rich pellets) occurs in minor percentage in some samples associated with varicoloured silty shale and bioturbated iron-rich shale lithofacies, and characterized by its oolitic texture between quartz grains in thin section of well A9-NC7A.



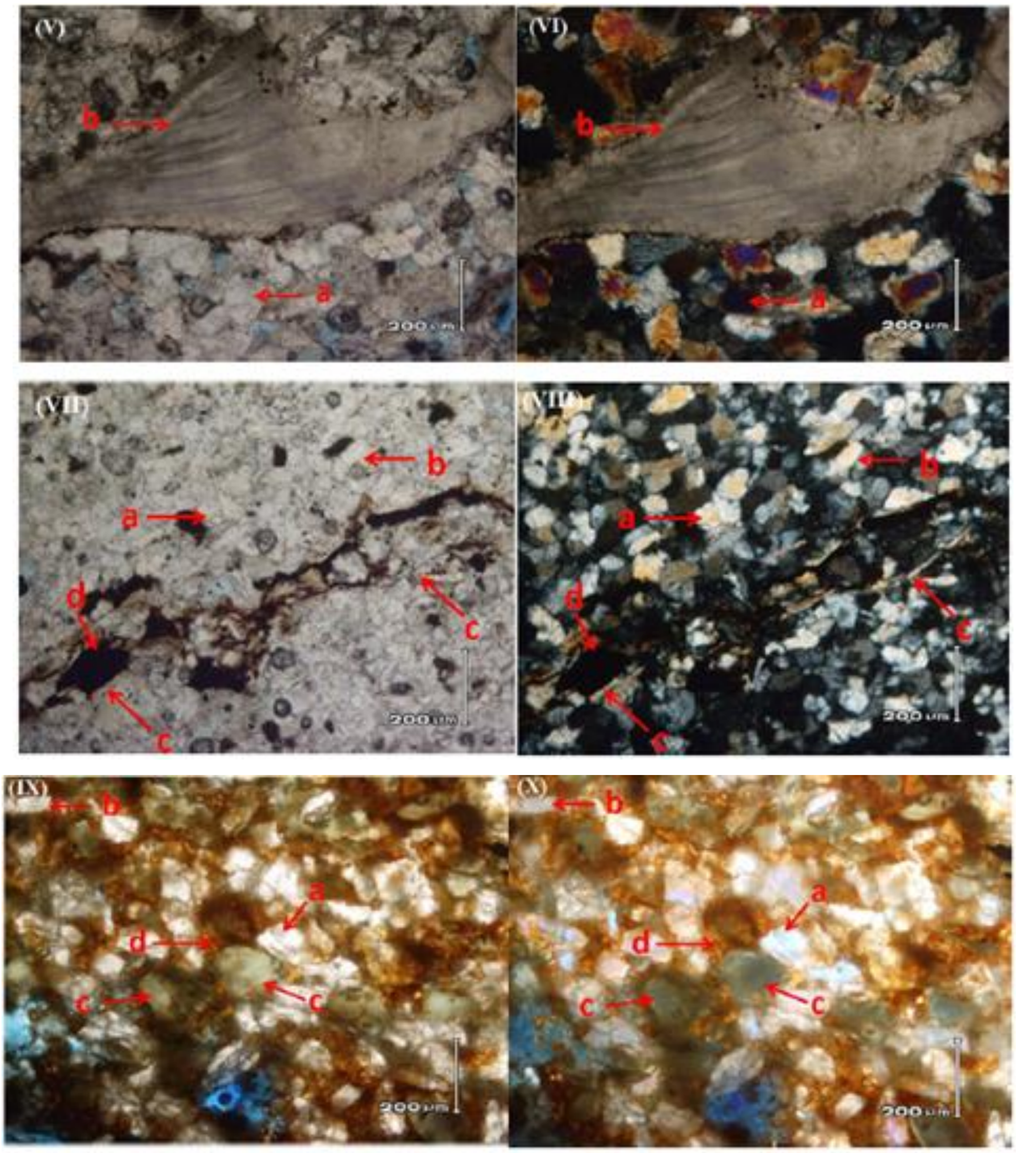


Figure10. *Microscopic photographs of the components of sandstones from the Tahara Formation. (I) Rippled and fossilliferous sandstone lithofacies, sublitharenite,*

showing (a) Quartz,(b) Feldspar and (c) Clay clasts. Core # 2 at 5782.2ft., well A12-NC7A (PPL). (II) Same as in thin-section(I) but in (XPL). (III) Rippled an fossilliferous sandstone lithofacieslitharenite, showing (a) Quartz, (b) Fossil fragment, Core # 3 at 5796ft., well A12-NC7A (PPL). (IV) Same as in thin-section (III) but in

(XPL). (V) Rippled and fossiliferoussandstone lithofacies, litharenite, showing (a) Quartz, (b) Fossil fragment, Core # 3 at 5796ft., well A12-NC7A (PPL). (VI) Same as I thin-section (V) but in (XPL). (VIIInterlaminated shale and silty sandstone lithofacies, sublitharenite, in Tahara Formation, showing (a) Quartz, (b) Feldspar, (c) Mica and (d) Clay clast, Core # 2 at 5435ft, Well F1-26 (PPL).(VIII) Same as in thin-section (VII) but in (XPL). (IX) Interlaminated shale and silty sandstone lithofacies, quartzarenite,

showing (a) Quartz, (b) Feldspar,(c)Glauconite and (d) Clay matrix and. Core # 2 at 5754.7ft., well A8-NC7A (PPL). (X) Same as in thin-section (IX) but in (XPL).

7.5. Cement

The Tahara sandstone composed mostly of well compacted quartz grains (grain to grain supported) straight contact through which a partial pressure solution silica cement is existed (Fig. 11; (1) & (2)), other quartz grains may show overgrowth between adjacent grains (Fig. 11; (3) & (4)).

Carbonate cement is less common in the Tahara sandstones. Characterized by golden yellow high order birefringence, rhombic cleavages occurs locally as patchy calcite filling pores ranging from 5% to 28% in quartz grain supported samples as calcite cement may be inferred to post-dated quartz overgrowths (Fig. 11; (5) & (6)).

7.6. Clay Matrix

Clay matrix comprises a low percentages of about 0 % in the massive sand and gravel lithofacies, while it is dominantly filling pore spaces with high percentages of about 34% in the interlaminated shale and silty sandstone lithofacies. Clay matrix may be generated by mechanical compaction of quartz and feldspar grains or as a result of bioturbation at some places (Fig. 10; IX , X, Fig. 11; (7) & (8)).Clay cement may be encountered as pore filling illite or replacive occasionally replaces kaolinite in sandstone (Fig. 11; (7) & (8)).

7.7. Porosity

Intregranular primary porosity total4% in the studied thin sections and mainly reduced by early quartz overgrowth (Fig. 11; (1(-(4), Fig.12; (1) & (2)). However, secondary porosity by dissolution and rock grains fractures is more dominating the studied thin sections, the primary constituents dissolved are rock fragments and feldspar grains (Fig. 12; (3)-(6)), where fractures is more common inbioturbated sand and shale lithofacies (Fig. 12; (7) & (8)) (see Table. 5).

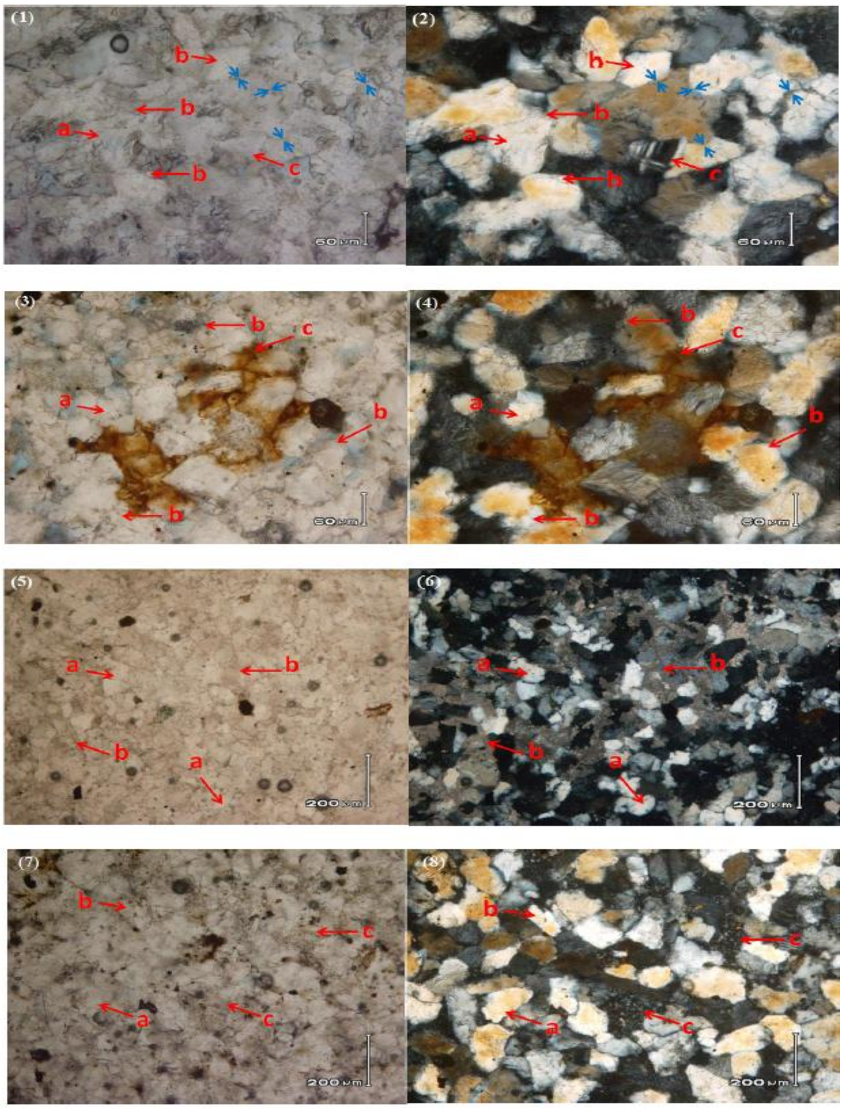


Figure11. *Detailed thin-section photomicrograph of massive sandstone and gravel lithofacies, quartzarenite, in Tahara Formation, showing (1): (a) Quartz, (b) Quartz overgrowth and(c) Feldspar. Blue arrows refer to pressure solution area Core # 3 at 5448.7ft., well F1-26 (PPL).(2): Same as in thin-section (1) but in (XPL).(3): (a) Quartz, (b) Quartz overgrowth and (c) Clay cement. Core # 1 at 5719ft, well A8-NC7A (PPL). (4): Same as in thin-section (3) but in (XPL). (5): Parallel laminated silty sandstone and silty shale lithofacies, quartzarenite, showing (a) Quartz, and (b) Calcite cement.Core # 1 at 6199ft., well X1-NC7A (PPL). (6): Same as in thin-section (5) but in (XPL).(7): Interlaminated shale and silty sandstone lithofacies, sublitharenite, showing (a)Quartz, (b) Feldspar and (c) Clay matrix (kaolinite). Core # 1 at 5703ft., well A9-NC7(PPL). (8): Same as in thin-section (7) but in (XPL).*

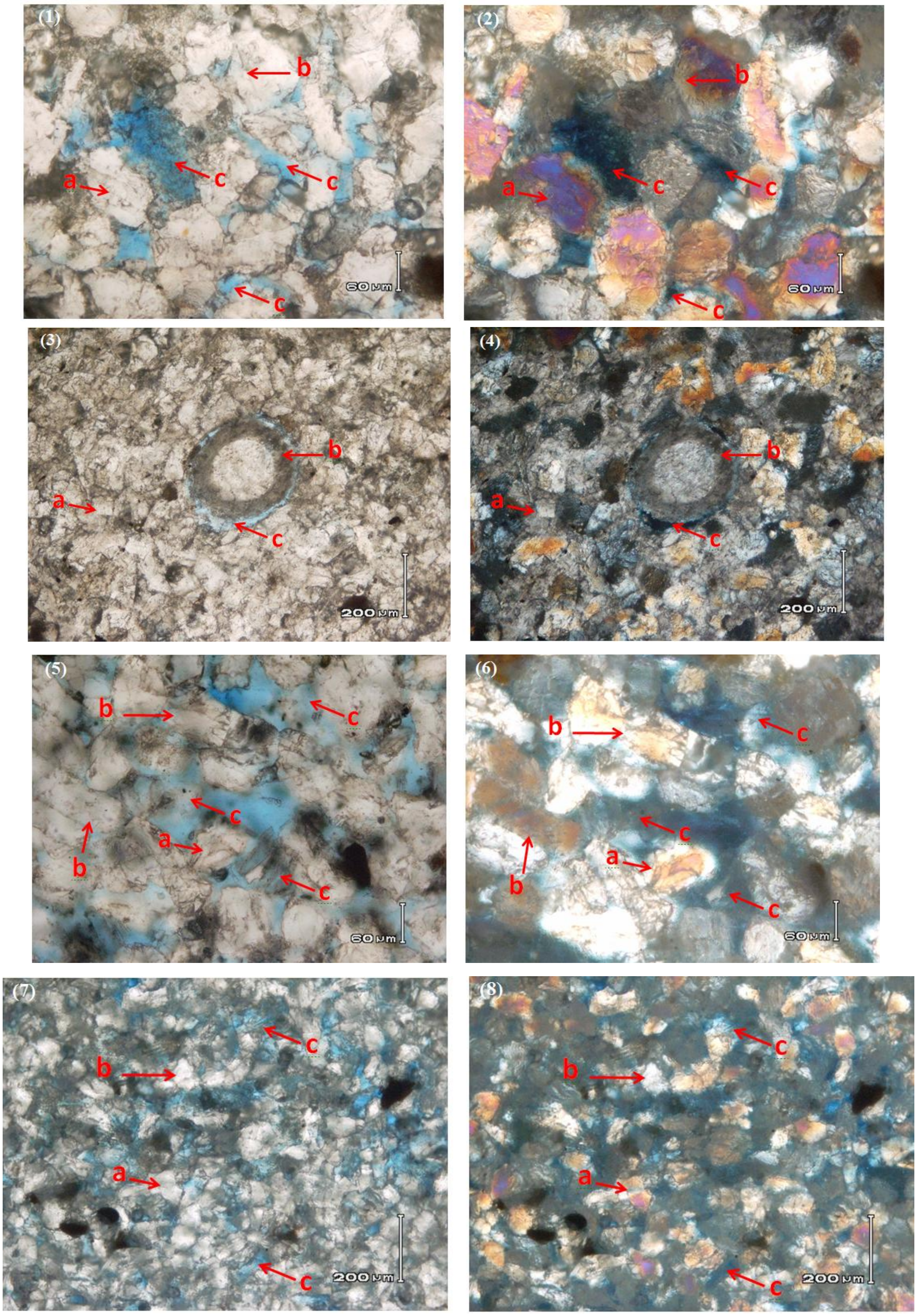


Figure12. *Detailed thin-section photomicrographs showing (1): Bioturbated sand and shale lithofacies, quartzarenite, showing (a) Quartz, (b) Quartz overgrowth and (c) Pore spaces.Core # 4 at 5790.11ft., well A8-NC7A (PPL). (2): Same as in thin-section (1) in which Quartz and feldspar grains (crystals) are varying in colors (from blue or violet to brown yellowish brown) show anomalous birefringencedue to thicker thin section (> 30 μm) (XPL). (3): Rippled and fossilliferous sandstone lithofacies, litharenite, showing (a)Quartz, (b) Fossil fragment, (c) Shrinkag dissolution porosity. Core # 1 at 5706.2ft., well A8-NC7A (PPL). (4): Same as in thin-section (3) but in (XPL). (5): Interlaminatedshale and silty sandstonelithofacies, subarkose showing(a) Quartz, (b) Feldspar of lath like shape and (c) Feldspar dissolution. Core # 4 at 5828.10ft.wellA12-NC7A (PPL).*

(6): Same as in thin-section (5) but in (XPL). (7): Bioturbated sand and shale lithofacies, quartzarenite, in Tahara Formation, showing (a) Quartz (b) Feldspar and (c)Leaching porosity due to partial dissolution of Feldspar grains.Core # 5 at 5820.7ft,,well A8-NC7A (PPL). (8): Same as in thin-section (7) but in (XPL).

8. MODAL ANALYSIS

Modal analysis for the examined thin sections of Tahara Formation was conducted as shown in Tables(2-5), where the result of this modal analysis was plotted on Ternary diagram (Fig. 13).

Table2. *Modal composition of thin section samples from Tahara Formation*

Slide No. Minerals	1	2	3	4	5	6	7	8	9
Quartz	250	284	288	136	210	255	256	282	257
Feldspar	2	1	3	2	4	3	4	6	4
Rock Fragment	30	15	9	2	26	38	35	1	28
Opaque Minerals	0	0	0	2	10	0	0	1	5
Mica	0	0	0	0	2	0	5	0	0
Glauconite	0	0	0	54	0	0	0	0	0
Heavy Minerals	0	0	0	0	0	0	0	0	0
Clay	0	0	0	104	48	4	0	10	6
Calcite	18	0	0	0	0	0	0	0	0
Chamosite (iron-rich sh. pellets)	0	0	0	0	0	0	0	0	0
Total	300	300	300	300	300	300	300	300	300

Table3. *Modal composition of thin section samples from Tahara Formation*

Slide No. Minerals	10	11	12	13	14	15	16	17	18
Quartz	134	129	223	138	254	262	196	199	265
Feldspar	2	3	7	2	3	25	1	6	6
Rock Fragment	162	138	1	0	29	9	102	18	29
Opaque Minerals	0	2	0	5	0	4	0	3	0
Mica	0	3	0	0	0	0	0	0	0
Glauconite	0	0	0	0	0	0	0	0	0
Heavy Minerals	0	0	0	0	0	0	0	0	0
Clay	2	25	35	80	14	0	1	3	0
Calcite	0	0	34	0	0	0	0	71	0
Chamosite (iron-rich sh. pellets)	0	0	0	75	0	0	0	0	0
Total	300	300	300	300	300	300	300	300	300

Table4. *Modal composition of thin section samples from Tahara Formation*

Slide No. Minerals	19	20	21	22	23	24	25	26	-	-
Quartz	192	238	253	259	250	234	267	230	-	-
Feldspar	2	5	5	7	3	1	2	3	-	-
Rock Fragment	20	8	27	10	25	27	30	4	-	-
Opaque Minerals	0	1	0	9	0	1	0	0	-	-
Mica	0	0	0	0	6	4	0	0	-	-
Glauconite	0	0	0	0	0	0	0	0	-	-
Heavy Minerals	0	0	0	0	0	0	0	0	-	-
Clay	2	10	15	0	16	33	1	63	-	-
Calcite	84	38	0	15	0	0	0	0	-	-
Chamosite (iron-rich sh. pellets)	0	0	0	0	0	0	0	0	-	-
Total	300	300	300	300	300	300	300	300	-	-

Table5. *Porosity types and percentages (%)*

Primary		Secondary		
Intergranular	Intercrystaline	Moldic	Solution	Fracture
4%	1%	4%	13%	0%
Total 22%				

9. DETRITAL COMPOSITION

The Tahara sands have a highmicrofracture quartz content, which constitute most of the Tahara sands for an average of about (86%) of the total sand grains, and an averageof about (2%) of feldspar grains. The remaining grains consist of average (11%) rock fragments which represented by clay clasts and fossil remains. Other minor constituents of an average ≤ 1% were recognized such as clay, calcite, glauconite, carbonaceous materials, and mica.On the basis of the ternary diagram of (Folk, 1980) [38], and after plotting of all studied thin sections (Fig. 13) the detrital composition of Tahara sandstone in Gullebi Field is that of sublitharenite to quartzarenite, with some few thin sections of litharenite and subarkose texture.

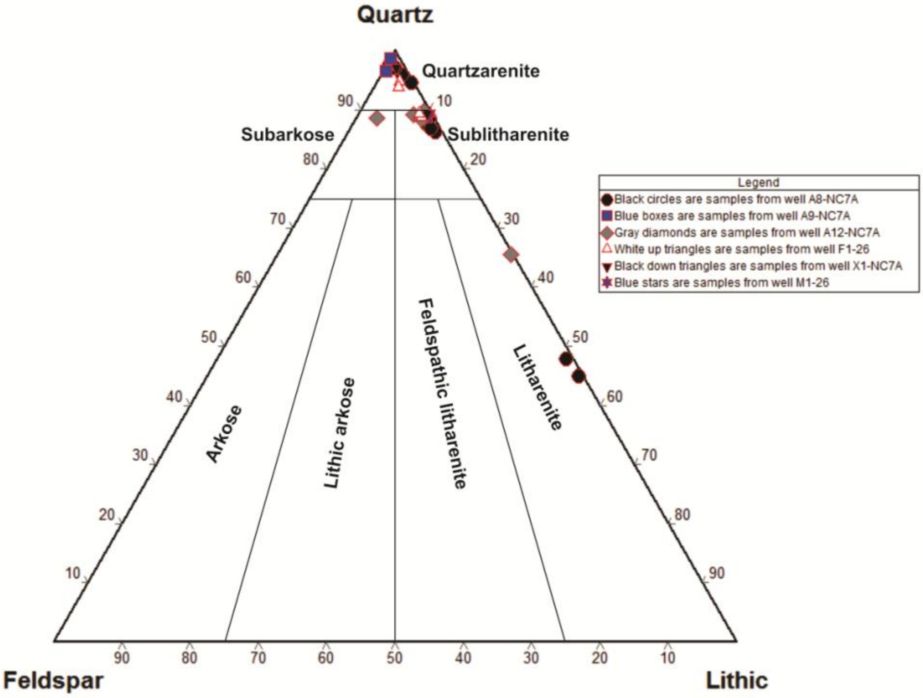


Figure13. *Detrital composition of sandstone thin sections of the Tahara Formation plotted in Ternary QFL diagram, (QFL classification of sandstones after Folk, 1980)[38].*

10. RESERVOIR LITHOFACIES ASSOCIATION

Based on petrography data and identified diagenetic constituents three (3) possible reservoir quality types or association can be identified for the Tahara sandstones which are:

1. The good quality lithofacies association (Fig. 14; (1) & (2)) consists of f-m grained sandstone, well sorted, quartzarenite (Sample No. 3) and of rare mud clasts (3%) and no matrix (0%). The total cementation in this lithofacies is up to (7%) composed mainly of quartz overgrowth (7%), with no clay filling pores (0%) and calcite cement (0%). The primary porosity is partially preserved and the secondary porosity was generated by grain dissolution with total porosity (14.6%).
2. Medium quality lithofacies association (Fig. 14; (3) & (4)) comprises f-v.f grained sandstone, well-poorly sorted, with feldspar to lithic primary composition (sublithic) (Sample No. 21) and of some mud clasts (9%) and matrix (5%). The total cementation in this lithofacies is up to (13%) composed mainly of quartz overgrowth (8%), clay filling pores (5%) with no calcite cement (0%). The primary porosity is partially preserved and the secondary porosity was generated by grain dissolution with total porosity (12.6%).
3. Low quality lithofacies association (Fig. 14; (5) & (6)) consists of silty-v.f grained sandstone, well-poorly sorted, with feldspar to lithic primary composition (sublitharenite) (Sample No. 24) with abundant mud clasts (9%) and matrix (11%). The total cementation in this lithofacies is up to (20%) composed mainly of quartz overgrowth (10%), clay filling totally pore spaces (10%) and no calcite cement (0%). The primary and secondary porosity are totally blocked (0%).

11. THE DIAGENETIC PHASES AND PARAGENETIC SEQUENCE OF TAHARA SANDSTONES

The initial pore network of newly deposited sediments and the quality of shallow buried reservoirs are generally determined by the environment of deposition. This dictates the grain characteristics, which in turn control porosity and permeability. During burial, diagenetic events will modify the original pore network of reservoir rocks. Four main diagenetic mechanisms affect reservoir quality: compaction, cementation, dissolution, and recrystallization. These mechanisms are controlled by the detrital composition of the rock, burial depth, burial time, burial temperature, pore fluids, and pore fluid pressure [39].

The Tahara sandstones show a variety of diagenetic phases where the mechanical and chemical compactions playing important role. The Tahara sandstones has undergoing by early mechanical compaction which reduced the primary porosity of Tahara sandstone by causing grains rotation and rearrangement into a tighter packing configuration.

According to (Morton-Thompson and Woods, 1993) [39] rocks that contain mechanically labile grains, such as clay clasts, altered rock fragments, or delicate fossils, are likely to experience a reduction in porosity and permeability as the ductile grains plastically flow into adjacent pore spaces.

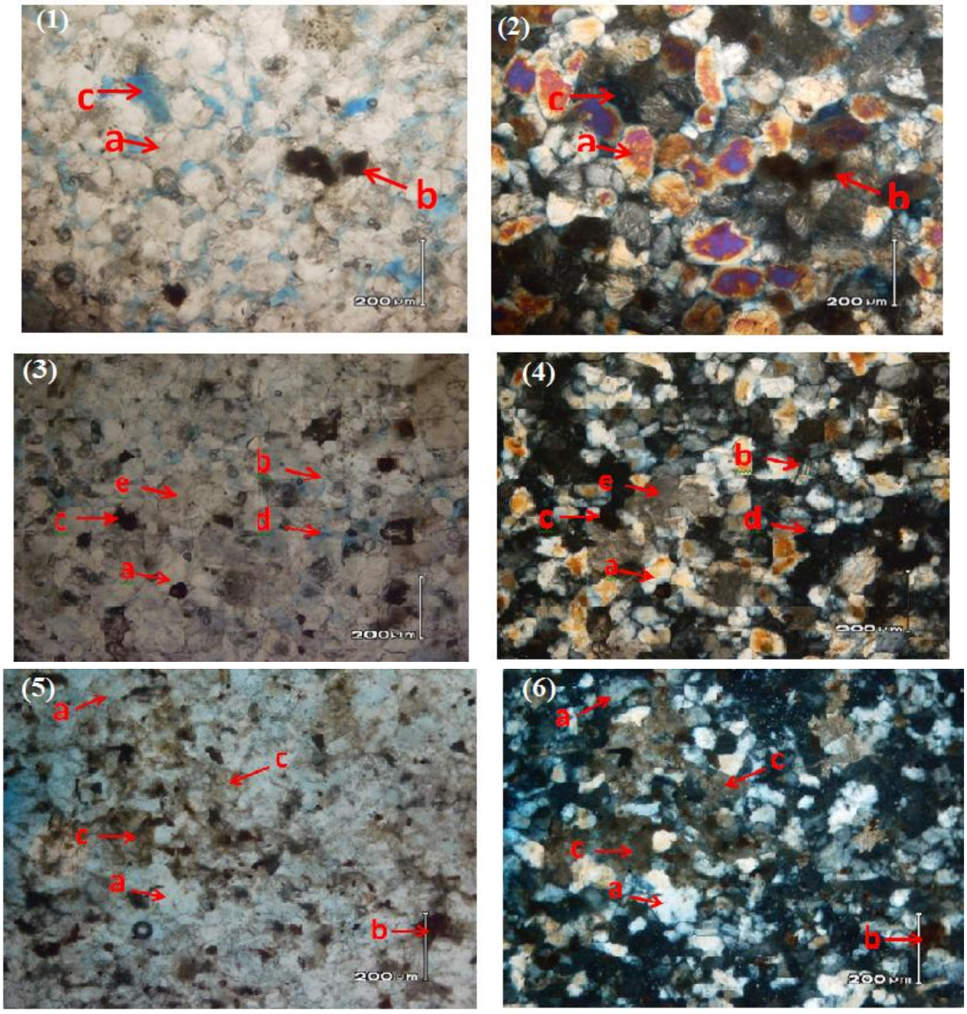


Figure14.*Thin-section photomicrographs the Tahara Formation, showing (1): Good quality lithofacies association in bioturbated sand and shale lithofacies, quartzarenite, (a) Quartz, (b) Clay clasts and (c) Pore space (partial primary andsecondary porosity). Core # 4 at 5790.11ft., well A8-NC7A (PPL). (2): Same as in thin-section (1) but in (XPL). (3): Medium quality lithofacies association in massive sandstone and gravel lithofacies, sublitharenite, showing (a) Quartz, (b) Feldspar, (c) Clay clasts, (d) Pore space (primary porosity is rarely preserved with some secondary porosity) and (e) Clay matrix filling partially pores. Core # 4 at 5502.11ft., well F1-26 (PPL). (4): Same as in thin-section (3) but in (XPL).(5): Low quality lithofacies association in interlaminated shale and silty sandstone lithofacies, sublitharenite, showing (a) Quartz with quartz overgrowth, (b) Clay clasts (filling partially pore spaces) and (c) Clay matrix (filling totally pore spaces). Core # 7 at 6205ft., well M1-26 (PPL). (6): Same as in thin-section (5) but in (XPL).*

Chemical compaction occurs by dissolution and precipitation of solids and are controlled by thermodynamics and kinetics (Fig. 15). Silicate reactions are very slow and sensitive to temperature. At temperatures above (80-100°C) quartz cementation and clay mineral alterations stiffens the rocks so that it siliceous sediments becomes "overconsolidated" preventing further mechanical compaction. Compaction at greater depth musttherefore be modelled as a function of temperature integrated over time [40]. Petrographically, according to the studied thin sections of the Tahara sandstone, we believe that the chemical compaction represented by authigenic quartz overgrowth had a great effect on the primary porosity reduction of the Tahara sandstone.

Another stage of chemical compaction represented by calcite cementation were noticed, and may have minor effect on the primary porosity of the Tahara sandstone because of their low percentage in the studied thin sections. This kind of cementation may results from transgression or subsidence post-dating quartz overgrowth, where the alkaline solution filling the pore spaces of the Tahara sandstone and precipitated the calcite cementin the remaining open pore spaces.

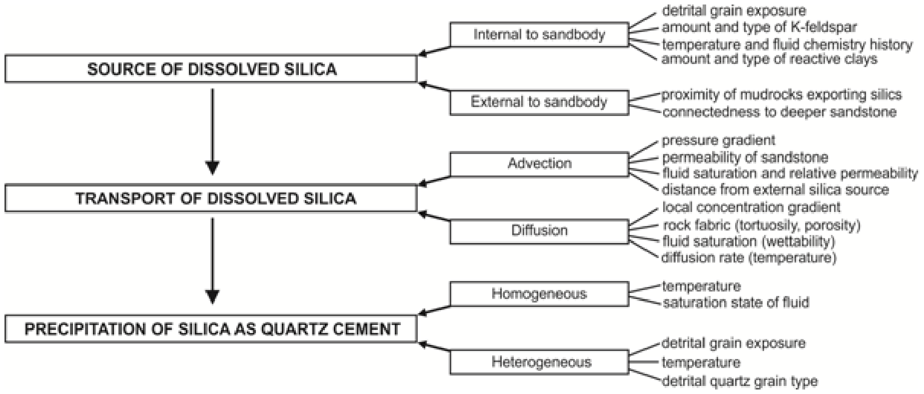


Figure15. *Schematic diagram for the geochemical controls on quartz cementation. The three fundamental controls are the rates of supply, transport and precipitation from aqueous solution. These have been subdivided into the key secondary controls and the main influences on the rate of these key secondary controls are listed on the right of the diagram [41].*

The presence of clay cement had a major influence on reservoir quality of Tahara sandstone, where considerable amount of clay cement (in the form of clay clasts) and matrix were observed filling pore spaces and micro fractures associated with low quality studied thin sections, and thus reducing porosity and permeability. However, early formation of some authigenic minerals can preserve the original porosity by protecting the rock from later degradation by compaction or cementation.

Dissolution of less chemically stable minerals in sandstones and carbonates can sometimes significantly increase both the rock porosity and the permeability [42]. Dissolution tends to be especially important in carbonates that are buried to shallow depths and sandstones that are deeply buried. The reservoir quality of the Tahara sandstones had been largely enhanced by the dissolution of feldspar, rock fragments (Fossil remains) and may be calcite cement, this may result from subaerial exposure to the rock which may be infiltrated by acidic water caused partial or completely dissolution of the labile grains forming secondary porosity.

Therefore, the petrographic analysis conducted in this study has showed that Tahara reservoir quality is mostly impacted by diagenetic processes through time. In the examined thin sections of Tahara sandstones the depositional texture does not vary significantly, since all studied rocks are very fine-fine grained (siltstone to fine sandstone). Loss of porosity occurred mostly due to matrix generation and partially to calcite cementation. So sandstone samples with more contents of lithic fragments displayed more porosity reduction (sample no. 24). On the other hand, sandstone samples with more feldspar and other labile grains showed higher secondary porosity by dissolution of these constituents. Quartz overgrowths were important for maintenance of primary porosity as they limited mechanical compaction at some early stages in the good quality lithofacies. From the other hand, they may enlarged at certain conditions and help to shut-down pores with increasing compaction and finally reducing primary porosity.

A composite paragenetic sequence explaining diagenetic events through time for the Tahara sandstone of Gullebi Field can be proposed (Fig. 16).

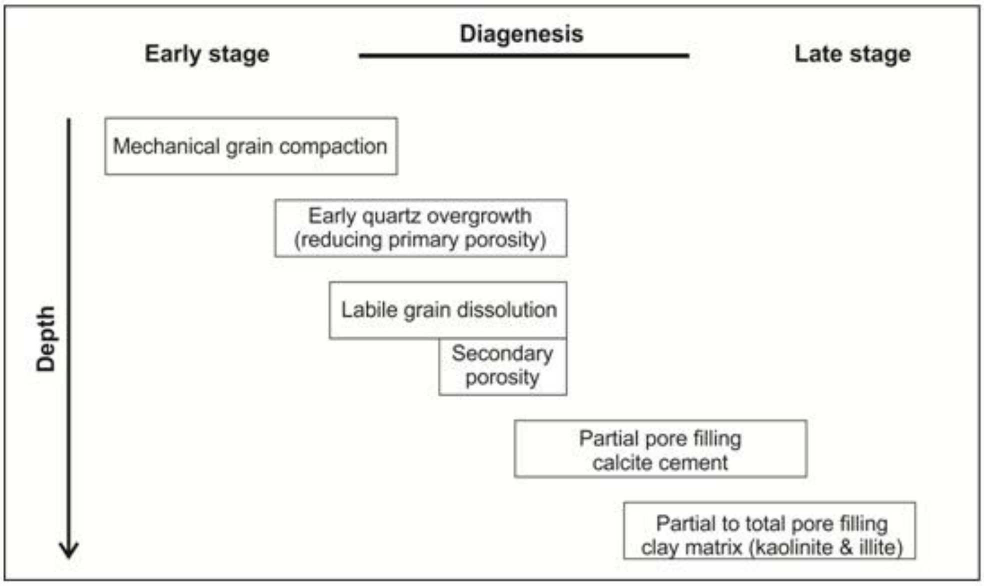


Figure16. *Paragenetic sequence for the Tahara sandstone in Gullebi Field.*

12. CONCLUSIONS

From this study we conclude the following points:

1. The Tahara sandstone consistspredominantly of fine to very fine, moderately-well sorted, cross laminated and rippled sandstone, with some silty shale interbeds and ferruginous beds with some thin beds of conglomerate contain plant materials and brachiopods fragments.
2. The Tahara Formation subdivided into seven (7) lithofacies on the basis of core analysis of the studied wells. It was also subdivided into lower and upper sandstone sequences on the basis of wireline-log characteristics.
3. Petrographic data shows that the Tahara sandstone can be classified mainly as quartzarenite-sublitharenite, with local litharenite and seldom of subarkose. The detrital mineral components are monocrystalline quartz, rock fragments and some feldspar.
4. The Tahara reservoir quality impacted by diagenetic processes through time; mechanical and chemical compaction(quartz overgrowth) reduced primary porosity, subsequent labile grain dissolution enhanced porosity (secondary porosity), loss of porosity again occurred mostly due to matrix generation and partially to calcite cementation.Sandstone units with more contents of lithic fragments has more porosity reduction. On the other hand, sandstone units with more feldspar and other labile grains showed higher secondary porosity by dissolution of these constituents.

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