Stratigraphic and Structural Factors Influencing the Characterization of Tahara Formation, in Gullebi Field, South of Concession NC7A, Ghadames Basin, NW Libya

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Abstract

This research presents the interpretation of data from well-logs , core samples and subsurface stratigraphic and facies maps obtained from the Gullebi Oil Field, concession NC7A, Ghadames Basin, NW Libya. The study aims at using well log approach in establishing the sedimentary lithofacies, their successions and environments of deposition in this field, and to find out the possible stratigraphic and structural factors that might influencing the development of sandstone units of the Tahara Formation.

The palaeodepositional environments in the field were deduced by combining gamma ray log trends with core data. Lithofacies interpretation was carried out using the gamma ray, effective porosity and resistivity logs obtained from 16 wells. Correlation technique was used to delineate the subsurface trends of these lithofacies.

Lithofacies identification shows that the entire well interval consists of sand, silt and shale. Four GR-log motifs representing different lithofacies were recognized in the study area: a funnel log shape representing beach to proximal deltaic lithofacies; a bell log shape representing fluvial channel lithofacies; a serrated to spiky log shape representing transgressive and deep marine slope to basinal shale/silt lithofacies and small scale irregular serrated log shape representing lagoonal-mud flat lithofacies.

Three reservoir lithofacies associations in the Tahara Sandstones were defined based on different compositions and diagenetic patterns, represent different reservoir qualities: good quality lithofacies associated with the transitional beach to proximal deltaic sandstones of fine to medium grained with total porosity of 20% and measured log-permeability 36md, medium quality lithofacies associated with fluvial channel sandstones, fine to medium grained, with total porosity 12% and measured log-permeability 7md, and low-quality lithofacies associated with marginal deltaic silty sandstones, silt to very fine grained, with total porosity 10% or even less with measured log-permeability 4md. The porosity and permeability are better developed in areas of sandstone units deposited in beach-deltaic environment.

By using the available well control points, isopach maps of the upper sand unit of the lower Tahara sequence and the upper sand unit of the upper Tahara sequence have been constructed and revealed that the accumulated thickness of both sand units is a function of available space to fill and the degree of shallowing or deepening of the associated depositional surface. Also regional log facies maps have been constructed for these two selected sandstone units to easily define the distribution of the representative lithofacies and to delineate the arbitrary boundaries characterizing these studied units of the Tahara Formation.

The stratigraphic factors that may influencing the development of the Tahara Formation are better explained by sea level changes reflected on depositional lithofacies types and sedimentation rates (thickness variations), the characteristic mineralogical composition of the studied sandstone units and the differences in diagenetic processes.

Other structural factors that may be influencing the deposition of the Tahara Formation related to paleostructural configuration of the Gullebi Field and the major NE-SW striking bounding fault parallel to the axial plane of the Gullebi anticlinal ridge.

Chapter (1)
Introduction

The Ghadames (Hamada) 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 (Hallett, 2002). Several discoveries were made in the following years including Bir Tlacsin (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).

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, Aouinet Ouenine 'A' and Ouan Kasa formations at A3-26, and gas in the Tahara and Aouinet Ouenine '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 Aouinet Ouenine 'A' Formation (Teknica, 1997).

The National Oil Corporation (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 (Teknica, 1997). Later the 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

1.1 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 wide of 5 km.

1.2 Scope of study and objectives.

The term stratigraphy, relates to the study of rock successions and the correlation of geological events and processes in time and space (Koutsoukos, 2007). It is a fundamental science of all geological studies, allowing reconstructing the sequences of events of earth history, and the evolution of life on earth (Koutsoukos, 2007). The term structure refer to the way in which the rock was disposed; the orientation of the strata, (strike and dip), its faulting and the rock arrangements that these characteristics create (Burt et al., 2008).

A sedimentary basin is an area of gently folded centripetally dipping strata. In tectonic basins facies trends and paleocurrents are unrelated to the basin architecture, indicating that subsidence took place after deposition of the deformed strata. In syndepositional basins, by contrast, the facies trends, paleocurrents, and depositional thinning of strata toward the basin margin all indicate contemporaneous movement. (Selley, 2000)

Sedimentary basins typically begin with a transgressive sequence (migration of the facies toward the land) and end with a regressive sequence (migration of the facies seaward), but they may have a long and complicated history (Chapman, 1983).

A facies sequence is a series of facies which pass gradually from one into the other. The sequence may be bounded at top and bottom by a sharp or erosive junction, or by a hiatus in deposition indicated by a rootlet bed, hardground or early diagenesis. A sequence may occur only once, or it may be repeated.

Facies distribution and changes in distribution are dependent on a number of interrelated controls; sedimentary processes, sediment supply, climate, tectonic, sea-level changes, biological activity, water chemistry, volcanism. The relative importance of these factors varies between different environments (Reading, 1986).

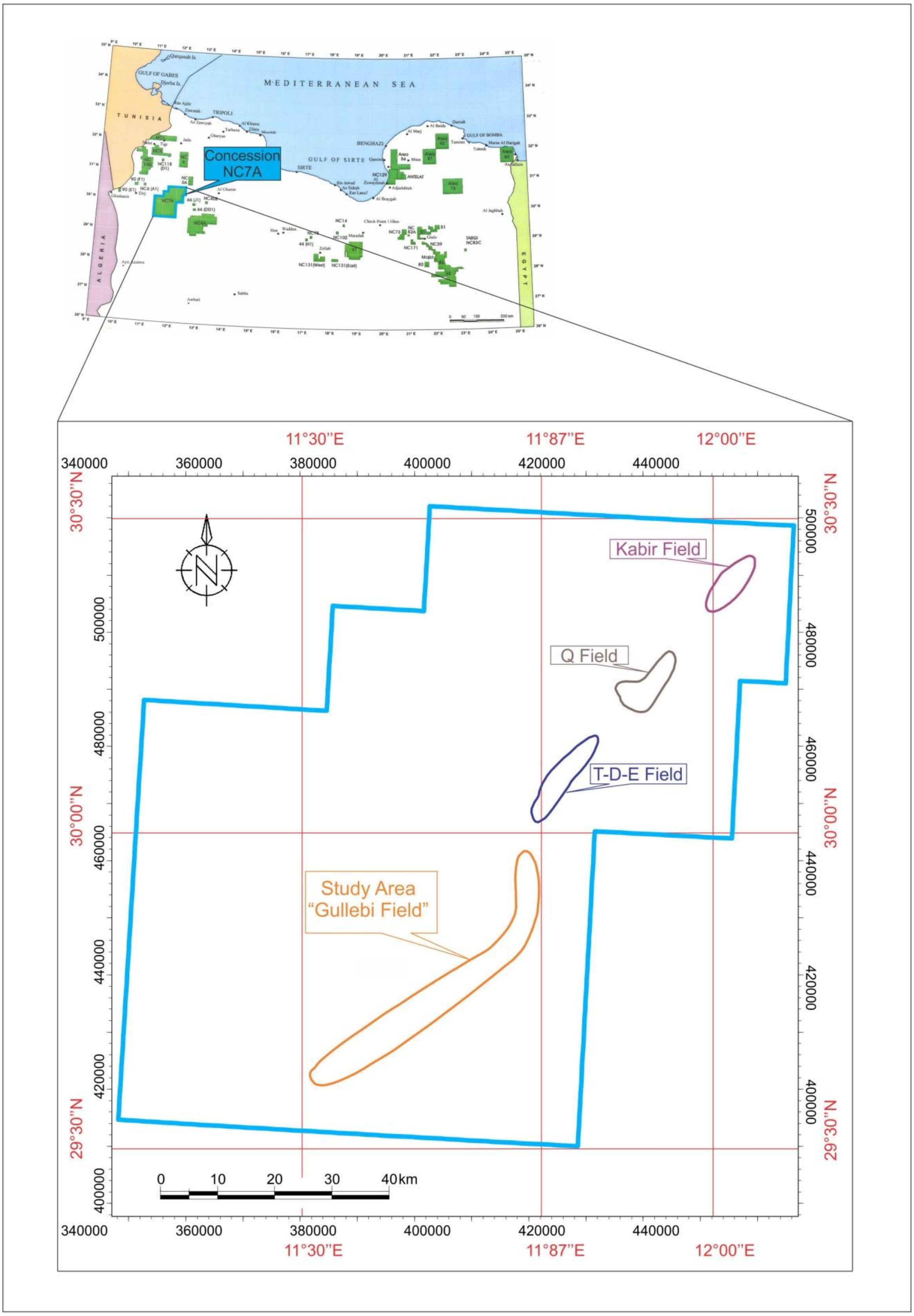


Figure 1. Location map of the study area (Gullebi Field, Concession NC7A).

The primary control on sediment accumulation is subsidence (assuming sediment supply) because sediment accumulation without subsidence is vulnerable to subsequent dispersal. The accumulation of a considerable thickness of sediment of the same facies merely reflects the constancy of the physiographic environments over the area of the sedimentary basin, the surplus sediment being removed (Chapman, 1983).

The rate of basin subsidence (owing to tectonism and sediment loading) together with rates of sea-level rise or fall control the available space in which sediments can accumulate (accommodation) as well as affecting sediment transport and deposition. Thus, owing to subsidence, thousands of kilometers of sediments may accumulate in shallow-water basins (Boggs, 1995).

The paleo-relief of the depositional basin may have a strong effect on the thickness and attitude of later sedimentary beds. Sediments deposited unconformably on an irregular surface adjust themselves by developing initial dips on the slopes and filling the valleys before the hills are buried. Hence, subsurface sections may show not only thinner intervals on structure, but inclined beds along the sides (Krumbein and Sloss, 1959).

The Upper-Devonian (Late Famennian-Strunian age), Tahara Formation, is considered to be the main productive reservoir in Gullebi Field at depth of 5500 – 5850 feet with thickness reaches to 150 feet. The numerous facies changes characteristics of the Tahara Formation, beside the lack of the informations about its strato-structural elements in the study area, causes to drilling of many dry boreholes, where poor reservoirs may be existed closer to good reservoirs as experienced for instance in the Gullebi Tahara pool. In the A4-26 well, the Tahara reservoirs were tight 2 km southeast of the productive A3-26 well. This makes the oil exploration on the level of the Tahara Formation within the study area unpredictable and risky, implying some heterogeneity in the reservoir quality of theses sanndstones.

In this thesis, we will shed light on thickness variations and stratigraphic continuity of Tahara Formation between studied wells, sandstone pinchouts, diagenesis and structurally high/low topographic areas. Thus, this research will help to define sandstone reservoir quality of the Tahara Formation and to assessing future exploration of these sandstones in the study area.

The main objectives of this study are:

a) To utilize well data to define lateral and vertical facies distribution of Tahara Formation across the Gullebi Field (Ghadames Basin).

b) To compare and contrast the characteristics of Tahara facies and to define possible stratigraphic or structural factors that may be influencing the characterization of Tahara sandstones.
c) To utilize the available well data for reservoir development and quality analysis of Tahara sandstone in Gullebi Oil Field of concession NC7A.

1.3 Previous work.

The first studies in Libya and in the Ghadames (Hamada) 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 Ghadames (Hamada) Basin were increased. The Paleozoic rocks were the main focus for most of these studies for their petroleum importance in the basin. Bellini and Massa (1980) 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.

The Palaeozoic and Mesozoic stratigraphy of eastern Ghadames and western Sirt basins were investigated by Belhaj (1996). Elruemi (2003) discussed the geologic evolution of Ghadames Basin-impact on hydrocarbon prospectivity, with cross sections and some maps, in addition of thins sections analysis. Abugares (2000) studied the petroleum geology of the Palaeozoic clastics of the Murzuq Baisn, Al Atshan saddle and the southern part of the Ghadames Basin, Libya. Beicip (1973) made a series of studies about Ghadames Basin including field trip reports, palynological, geochemical and economic studies.

Regional study of Ghadames Basin “analysis and evaluation” conducted by Maria (1991), 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. Echikh and Suleiman (1982) conducted a preliminary geological study and petroleum evaluation of Ghadames Basin, Libya. Arduini et al., (2003) studied the Silurian-Devonian sedimentary geology of the Libyan Ghadames Basin.

Sikander (2003) made a study about structural development, geology and hydrocarbon potential of the Ghadames and Murzuq Basins, another study by Sikander etal., (2003), where the geochemical source-maturation and volumetric evaluation of Lower Palaeozoic source rocks in the west Libyan Basins have been studied. Echikh (1998) discussed the geology and hydrocarbon ocurrences in the Ghadames Basin within Algeria, Tunisia and Libya. Bracaccia et al., (1991) studied the sedimentology of the Silurian-Devonian series in the southeastern part of the Ghadames Basin. Underdown etal., (2007) 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.

Elfigih (2000) 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, Ghadames (Hamada) Basin, north western Libya. Boote etal., (1998) discussed the Palaeozoic petroleum systems of North Africa. Hallett (2002) finished a book about petroleum geology of Libya, where all depositional basins in Libya had been discussed in details. Ghori and Mohammed (2003) made a petroleum system modelling study in Ghadames Basin. Shah et al., (1993) 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.

Regarding the Tahara Formation, a study was conducted by Ali(1977) 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. Another study was conducted by Hassi (1993) 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.

The Arabian Gulf Oil Company (AGOCO) has conducted an exploitation evaluation study in the Gullebi Field in 1997 (Teknica reports) containing some cross-sections and maps for the Paleozoic reservoirs including Tahara Formation. Some other studies have been conducted on the level of Tahara Formation in some other local areas including; Burki and Turner (2003) discussed the hydrocarbon reservoir potential of the Tahara Sandstones, Ghadames Basin, western Libya. El-Rweimi (1991) studied the geology of the Aouinet Ouenine and Tahara formations, Al Hamada Al Hamara Area, Ghadames Basin. He found that the sandstone of the Tahara Formation were deposited in transgressive marine environment. El-Mehdawi (2000) studied the palynology of the Upper Tahara Formation in concession NC7A, Ghadames Basin, and concluded that the studied Tahara section in wells AA5, AA6, AA10 and II1-NC7A is predominated with terrestrial over marine taxa suggests deposition in marginal marine to nearshore environment (fluviatile-deltaic environment)

To date the stratigraphic and structural factors controlling the Tahara Formation in Gullebi Field remain unknown, so as a part of this thesis we will try to address these factors and their effects on the reservoir quality variations.

Chapter (2)
Regional Geology of the Ghadames (Hamada) Basin and study Area

2.1 Regional tectonic settings

The Ghadames (Hamada) 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 (Belhaj, 2000).

2.1.1 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” (Unrug, 1997 in Hallett, 2002). 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. (Vail, 1991 and Schurmann, 1974)

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. 3). (Hallett, 2002)

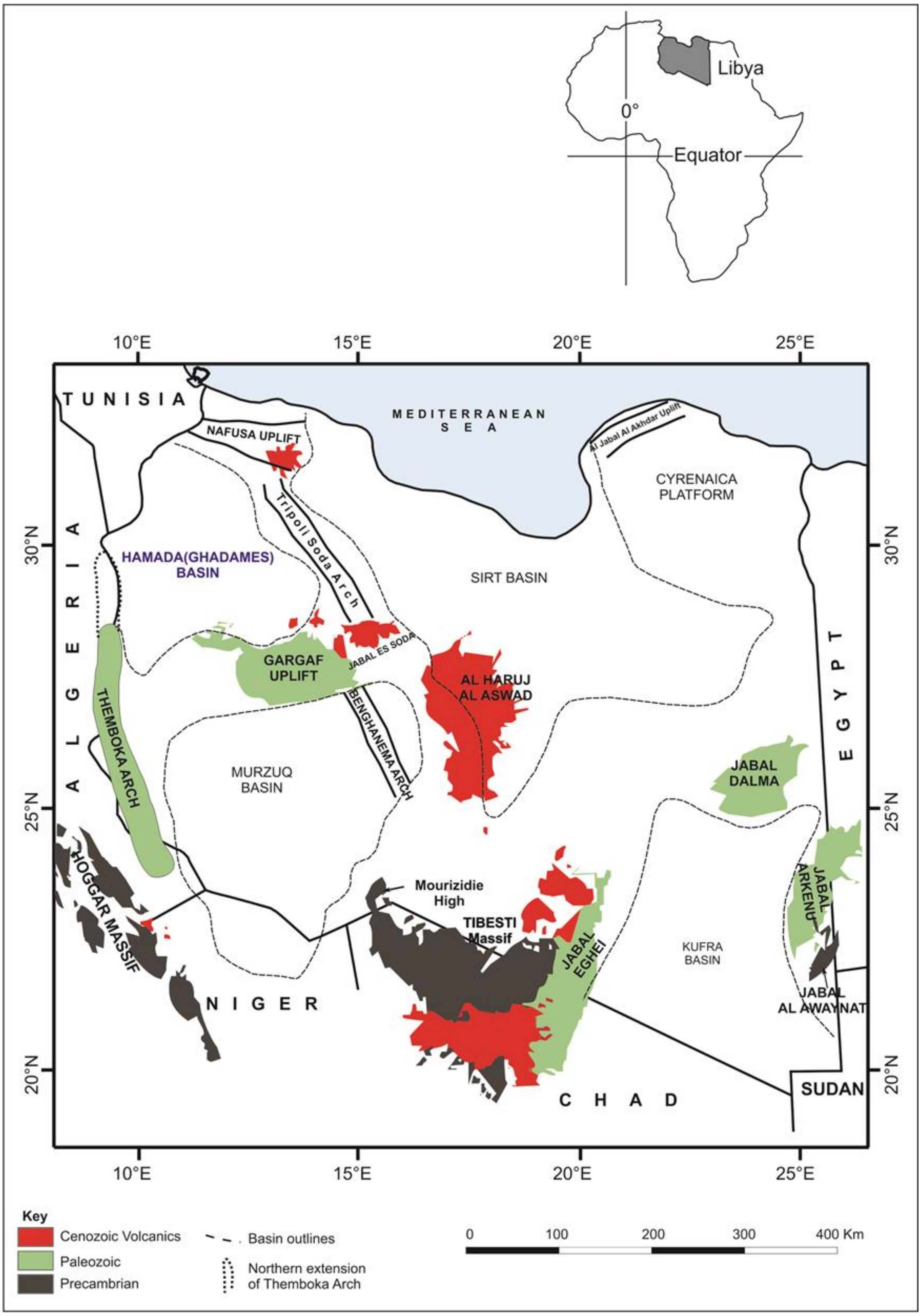


Figure 2. Ghadames (Hamada) Basin, regional boundaries and tectonic element of Libya. (modified after Elfigih, 2000).

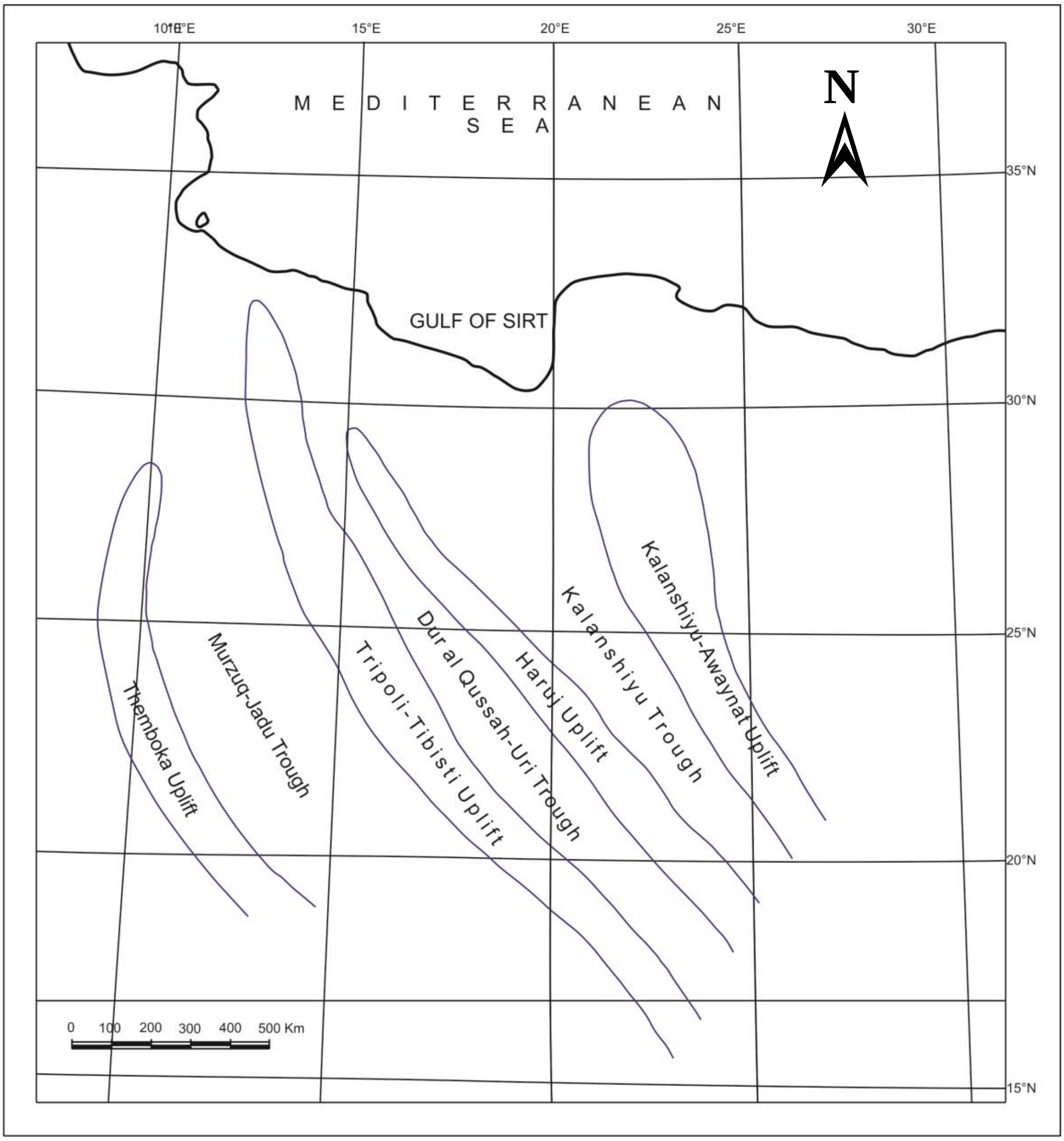


Figure 3. Paleogeographic map of Libya, showing Pan-African structures that formed during late Precambrian to Late Carboniferous tectonism. (after Klitzsch, 1971)

2.1.2 Paleozoic

The sedimentation during the Cambrian period was controlled by the mature relief and tectonically stable platform, which was inundated by very shallow seas (Mamgian,1980). 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 (Hassauna Sandtone) 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 (Melez Chograne 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 Taconian tectonic, 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 (Bertello et al., 2003).

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. 4). 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 Ghadames (Hamada) Basin.

Result of the collision between West Africa and North America. This caused the uplifting and erosion of the southwestern and southern flank of the Ghadames Basin, where the Lower Devonian (Tadrart) is seen to directly overly the Upper Silurian (basal Acacus).

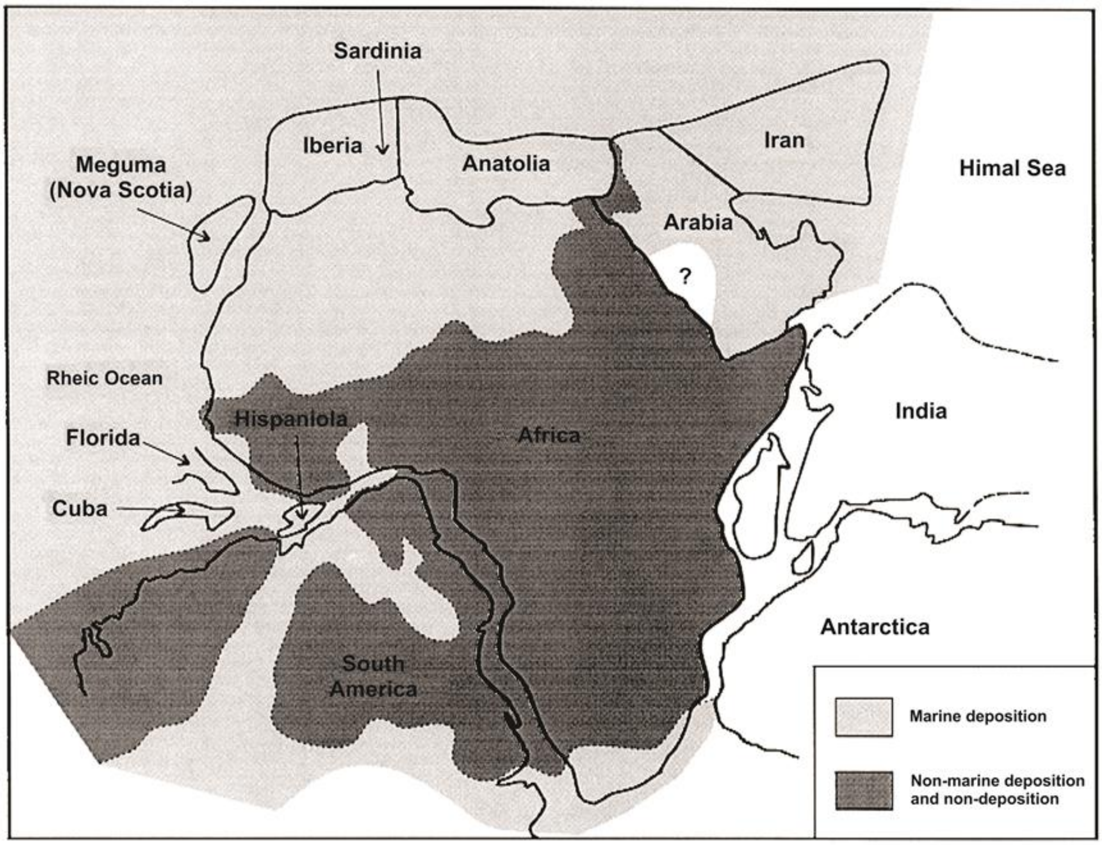


Figure 4. Early Silurian palaeogeographic map of Gondwana. (after Luning et al., 2000)

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) (Echikh, 1998). The subsequent Devonian succession includes the transgressive shallow marine sands of the Ouan Kasa Formation, and the Aouinet-Ouenine Formation.

The basin was gently uplifted during Late Devonian time corresponding to the Acadian Orogeny (Belhaj, 1996). 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. 5), 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. 6), 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 (Hallett, 2002).

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 (Hallett, 2002). 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. 7).

2.1.3 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 Ghadames 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

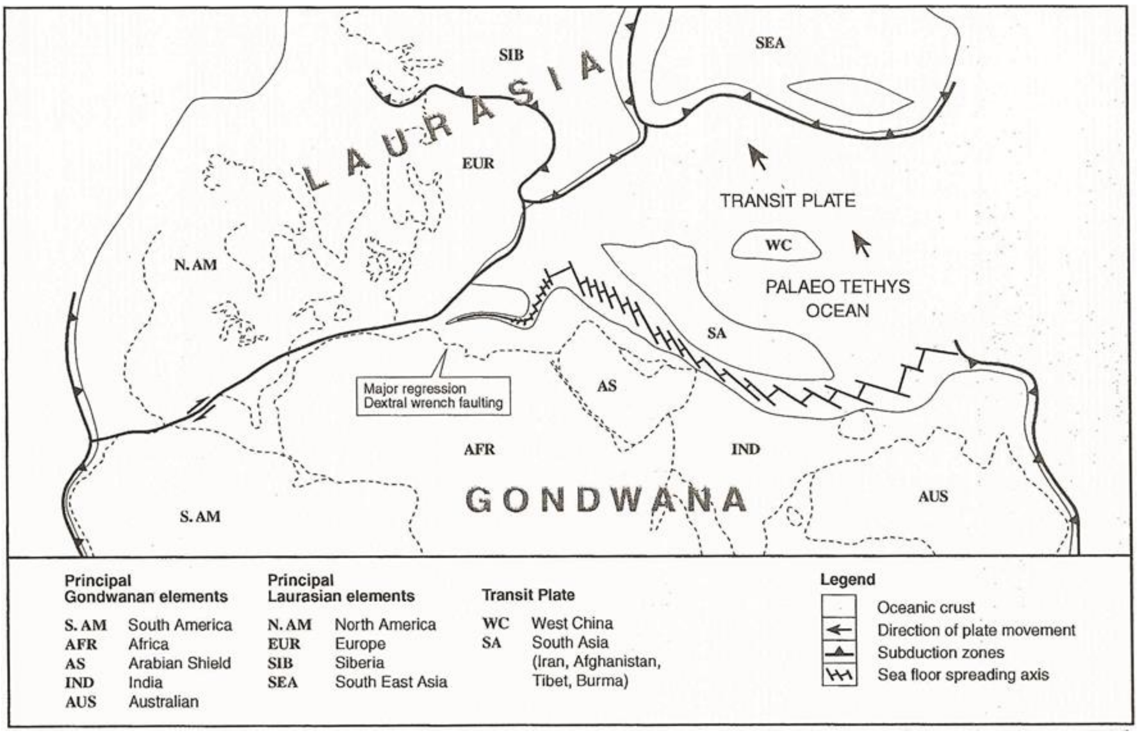


Figure 5. Hercynian compression as result of Late Carboniferous plate collision between Laurasia and Gondwana. (after Hallett, 2002)

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 (Boote et al., 1998).

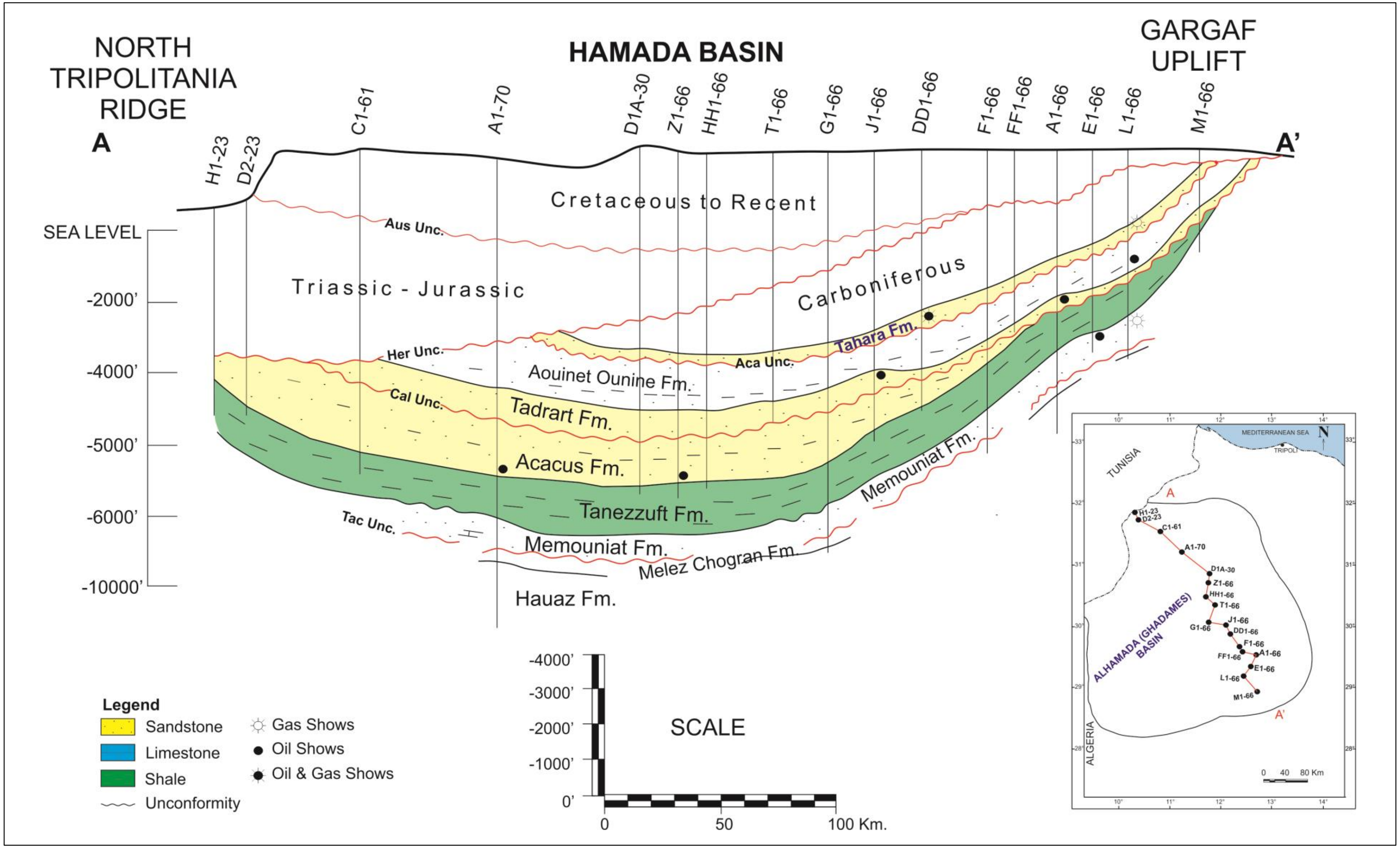


Figure 6. Regional NW-SE structure cross section in Ghadames (Hamada) Basin. (after Elfigih, 1991)

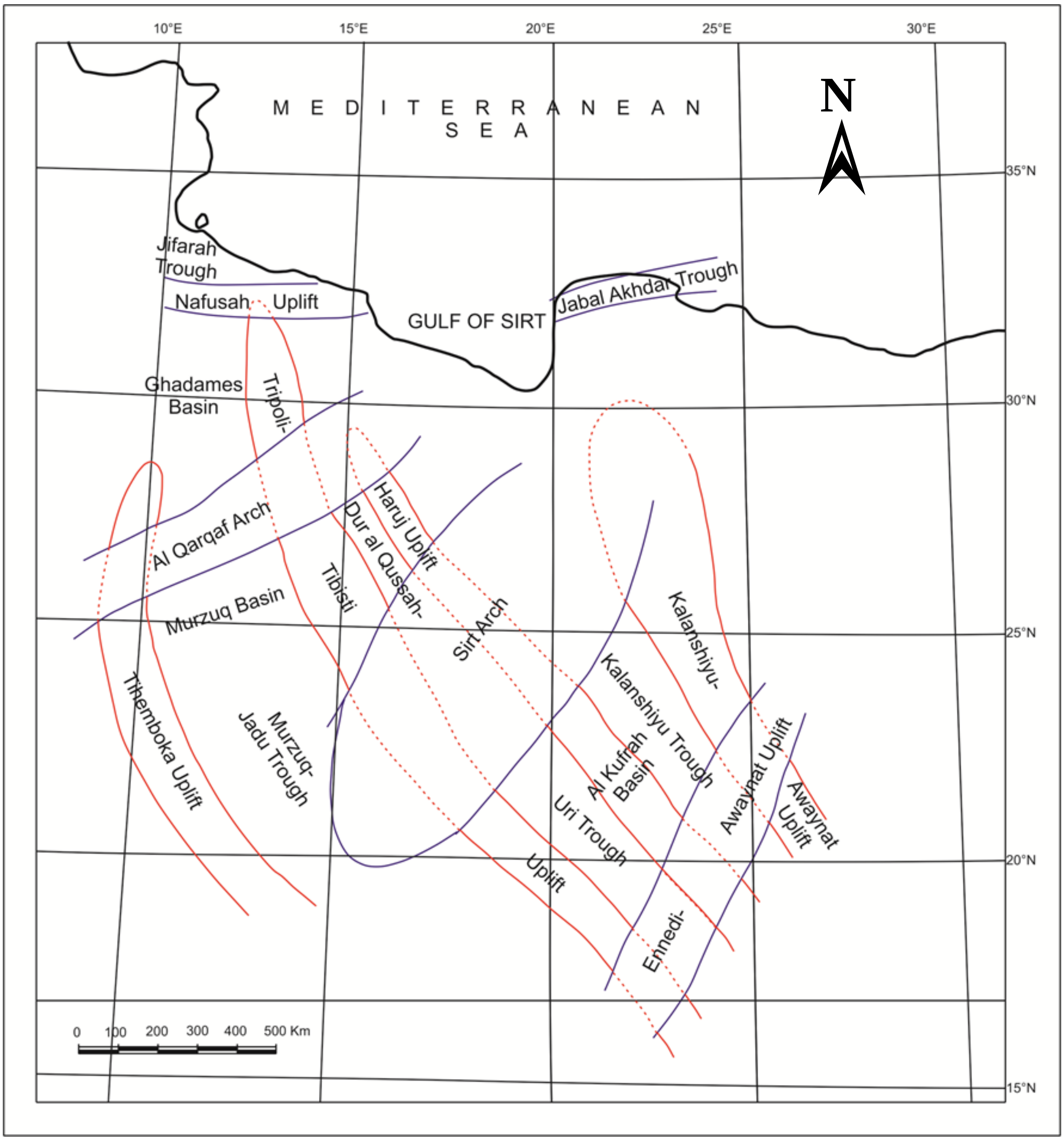


Figure 7. Paleogeographic map of Libya, showing Hercynian structural trends caused by the Late Carboniferous collision between Gondwana and Laurasia. (after Klitzsch, 1971)

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) (Underdown, 2006 in Underdown and Redfern, 2007). 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 (Elruemi, 2003).

2.2 Regional stratigraphic settings

Before the arrival of the oil companies and the begging of oil exploration in Libya, large part of the stratigraphic framework of the Ghadames Basin where established from the margins of the basin where the Paleozoic and the Mesozoic rocks crop out. Many type sections of these rocks have been described, this were supplemented by the subsurface data after the begging of oil exploration, and up to day many papers where published about the stratigraphy of the Ghadames Basin. Although there is a large number of unpublished works carried out by the operation oil companies within their blocks considered as internal company reports.

The first lexicon of stratigraphic nomenclature in Libya was compiled by Burollet (1960), followed by another geologists of oil companies (Compagnies Pétrolieres, 1964 in Tawadros, 2011). Because there has been little exchange of geological data between the countries where the Ghadames Basin extended and Libya, some of the nomenclature used in the stratigraphic nomenclature of Libya is difference from those used in these countries. In addition the formation boundaries have not been selected at the stratigraphic level, and the true lateral distribution of individual units and their bounding surface are difficult to follow over national border (Belhaj, 2000).

The sedimentary record of the Ghadames cratonic basin and nearby regions from Upper Precambrian to Late Paleozoic is divided by five major unconformities (Fig. 8). 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 (Maria, 1991; unpublished AGOCO report). The timing of the unconformities represented are:

(1) Late Carboniferous-Early Permian (Hercynian Unconformity).
(2) Late Devonian-Early Carboniferous (Acadian Unconformity).
(3) Late Silurian-Early Devonian (Caledonian Unconformity).
(4) Late Ordovician (Taconian Unconformity).
(5) Early Cambrian (Pan African Unconformity).

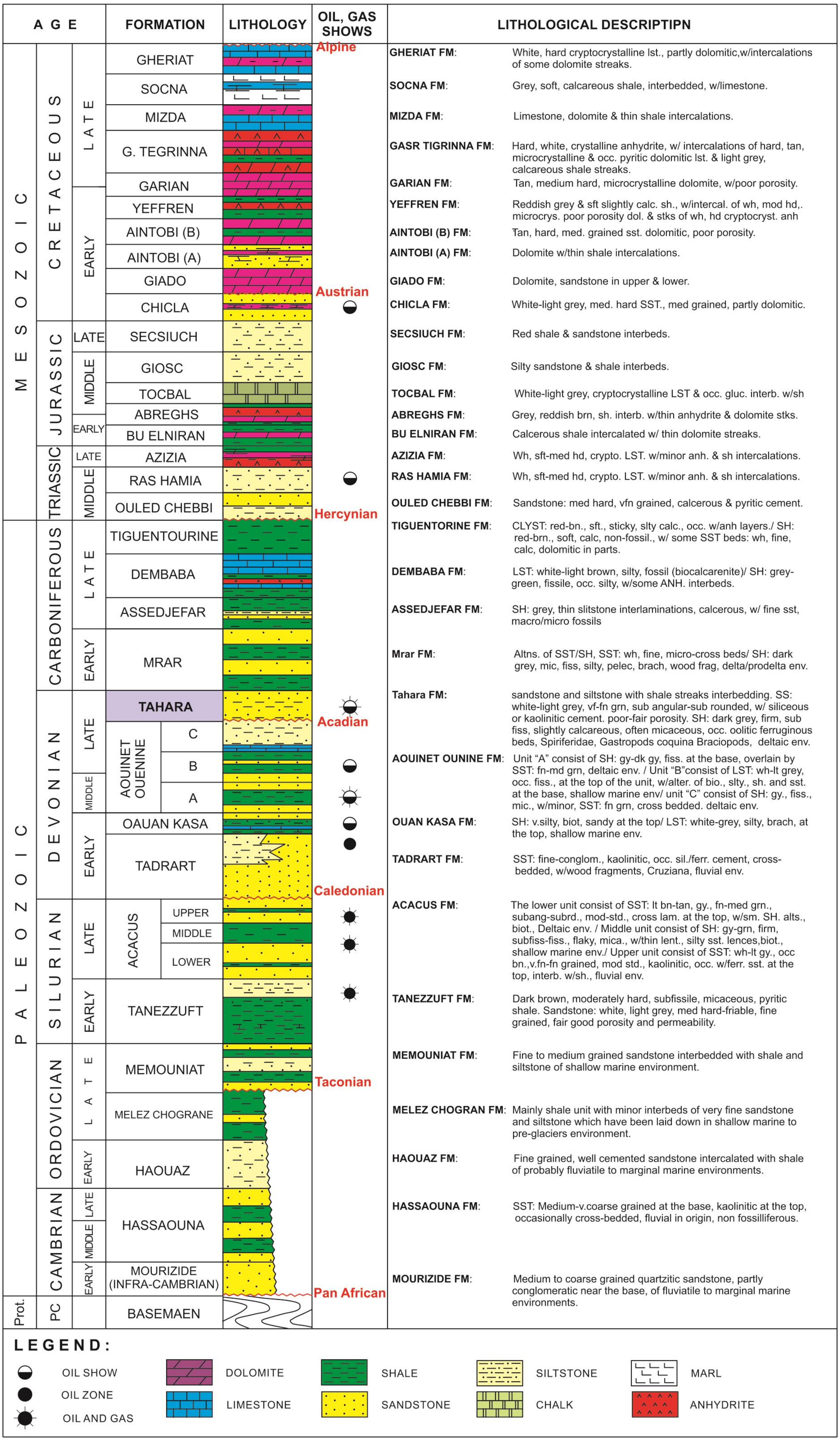


Figure 8. Lithostratigraphic chart of Ghadames (Hamada) Basin, Libya. (modified after Exploration Department-AGOCO, 2011).

The Palaeozoic outcrops in Libya are restricted to the southern part of the country covering an area of 200,000 Km^2 in parts of Hamada, Murzuq and Kufra basins (Mamgain, 1980).

2.2.1 Mourizidie Formation (Early Cambrian)

Burollet etal., (1963b) proposed this name for a sequence of red and violet sandstones, quartzitic arkoses and quartzitic lying unconformably over the folded metamorphic Precambrians (Pharusian) in the region of Mourizidy in the eastern Murzuk basin (Banerjee, 1980).

The Mourizidie is discordantly covered by the basal conglomerate of the Cambrian Hassaouna Formation of the Gargaf Group. The thickness is about 328 to 656 ft (100 to 200 m) in type locality of Mourizidy. These rocks are relatively flat lying and free of fossils (Banerjee, 1980). They are intensely folded along NNE striking tectonic axes and are intruded by synorogenic to late orogenic granites. Some authors think that this formation is infracambrian (Burollet etal., 1963b).

Some deepest wells of the Ghadames basin penetrated a distinct formation, whose lithologic characteristics as well as position between the Precambrian basement and the Hassaouna, compare easily to the Mourizidie formation (Beicip, 1972). The Mourizidie Formation was also penetrated in well Dl-NC 115 in the northern Murzuq Basin where it is 147ft (45 m) thick (Jacque, 1962 in Hallett, 2002).

Beicip (1972) suggested that Mourizidie Formation represents the first Cambrian filling of the basin, based on it is presence in the deepest and sinking parts of the basin and its absence near and on the boundering arches (Gargaf Tihemboka).

2.2.2 Gargaf Group

The Gargaf Group consists of interca1ated continental sandstone, conglomerate, and shale. Unconformities of erosion and nondeposition occur commonly within the group. The group is divided into four formations (Massa and Collomb, 1960): the basal Hassaouna of Cambrian age, and the Haouaz, Melez Chograne and Memouniat Formations of Ordovician age. The estimated overall thickness of the Cambrian and Ordovician rocks is between 2460-2624ft in the Gargaf area (Goudarzi, 1970).

2.2.2.1 Hassaouna Formation (Middle – Late Cambrian)

The name was first introduced by Massa and Collomb (1960) after Jabal Hassaouna which is a local name for the Jabal Gargaf, a mountaineous mass between 27°50’N and 28°45’N latitudes and 13°00’ and 14°40’E longitudes constituting the type locality (Banerjee, 1980).

According to (Massa and Col1omb, 1960) the formation is uniform sandy complex about 1148 to 1312ft (350-400 m) thick consists of a brown to yellowish-brown massive medium to coarse-grained highly crossbedded silicified sandstone with abundant conglomeratic lenses, containing Tigillites in its upper few meters. Kaolinitic cement and interbedded minor micaceous shale beds are characteristic.

It is unconformably overlain by the fine-grained sandstone of the Haouaz Formation of Ordovician age and overlies the Precambrian metamorphosed rocks and granites with strong angular unconformity (Goudarzi, 1970). In some places this formation is intruded by volcanic rocks, (dolerite sills and gabbros have been drilled in Al-66 and in Al-70 in the Ghadames Basin of Libya (Beicip, 1972).

The Hassaouna Formation represents a homogeneous sedimentation of “extensive blanket sand” type spread over the entire Sahara, with consistent paleocurrent directions towards the north and northeast. It is deltaic or perhaps fluviatile in nature (Burollet and Byramjee, 1969 in Banerjee, 1980).

The Hassaouna Formation is well developed in the Dur al Qussah Trough. On the flank it has a thickness of 1968 ft (600 m) and is extremely conglomeratic and contains abundant kaolin, but it thickens rapidly into the trough where it reaches a thickness of 5577ft (1700m) (Klitzsch, 1963&1971 in Hallett, 2002).

In the Ghadamas Basin, the environmental deposition appears to be largely of continental, fluviatile, marginal marine origin (Maria, 1991; unpublished AGOCO report).

2.2.2.2 Haouaz Formation (Early Ordovician)

The term was introduced by Massa and Collomb (1960) after Jabal Haouaz (28° 15’N: 13° l5’E) in the western part of Jabal Gargaf (Banerjee, 1980). This formation represents the lowest part of the basal transgressive unit of the Ordovician-Silurian sedimentary cycle (Maria, 1991; unpublished AGOCO report).

The formation consists of thin to thick bedded fine grained quartz sandstone, interbedded with silty micaceous, shale beds characterized by the presence of many Tigillite beds and abundant ripple marks. The thickness is about 918 ft (280 m) thick in the Jabal

Gargaf region, and approximately 164 ft (50 m) in the northern Dor el Gussa where it wedges out southeastward between the Hassaouna and the Melez Chograne Formations (Banerjee, 1980).

The Haouaz Formation was penetrated by several wells in Ghadames Basin. Its stratigraphic relation with other Cambro-Ordovician Formation is not clear. The Haouaz Formation may have a shallow to continental environment (Echikh and Suleiman, 1982).

The Haouaz Formation overlies the Cambrian Hassaouna Formation with a strong unconformity seen in the Murzuk basin (Klitzsch, 1963). This unconformity is not very apparent in the Jabal Gargaf area (Massa and Collomb, 1960). The upper contact passes concordantly to the overlying Melez Chograne Formation (Banerjee, 1980).

Collomb divided the Haouaz Formation into three subdivisions, an upper Tigillites sandstone, a middle coarse sandstone and a lower 'Tigillites sandstone.(Massa and Collomb, 1960& Collomb, 1962), in (Hallett, 2002). The two lower parts are sometimes named “Achebyat Member” and considered as the upper part of the Hassaouna formation (Beicip, 1972).

The Haouaz Formation is deposited in less agitated water (low energy) and is well bedded. The Caledonian epeirogenic movements started during this time causing the fragmentation of the sedimentary basins often presenting a more marine character. Sediment transport directions are then more diversified with frequent facies changes, distinctly more dependent on local factors as trough structures or basin formations (Burollet and Byramjee, 1969 in Banerjee, 1980).

The Haouaz Formation on the Al Qarqaf Arch, as redefined, comprises 393 ft (120 m) of alternating siltstones and thinly bedded, cross-bedded sandstones with abundant Tigillites. Vos interpreted this sequence as a coarsening-upwards delta front/delta top highstand deposit (Vos, 1981b in Hallett, 2002). The depositional environment was shallow marine and the presence of Tigillites suggest occurrences of tidal flats (Beicip, 1972).

2.2.2.3 Melez Chograne Formation (Late Ordovician)

The term was introduced by Massa and Collomb (1960) after the Melez Chograne Mountain (28° 20’N: 13° 00’E) in the western part of Jabal Gargaf (Banerjee, 1980). It included glacial deposits occurring over a large area in the central Sahara region, around the margins of the Hoggar and Tibesti massifs (Maria, 1991; unpublished AGOCO report).

The Melez Chograne is an argillaceous sequence consisting of varicoloured green and purple, chloritic, thin bedded shale intercalated with fine grained micaceous sandstone and siltstone. Big blocks of granite, gneiss, quartzite, polished and striated pebbles showing glaciation and iceberg transportation are included in the formation (Collomb 1962). In the middle part of it is a bed of violet-brown shale which is richly fossiliferous. The unit is 32 to 196 ft (10-60 m) thick (Banerjee, 1980).

In the Dor el Goussa area, the Melez Chograne is a silty and sandy, gray and reddish shale about 82 ft (25 m) thick and has fine grained sandstone intercalations. It overlies the Haouaz Formation in northwest Dor el Goussa, the Hassaouna Formation in the southeast, and is generally absent in the eastern flank (Klitzsch, 1963 in Goudarzi, 1970).

The lower boundary is with angular unconformity on the Cambrian Hassaouna Formation, or continued to the Lower Ordovician Haouaz Formation probably by transgression (Collomb 1962). The upper boundary is erosive and discordant with the Upper Ordovician Memouniat Formation (Klitzsch, 1963 in Banerjee, 1980).

The lower boundary of the Melez Chograne Formation around the south—west part of the Ghadames Basin region is represented by a close pattern of paleovalleys, cutting deeply by a large continental ice sheet into the older deposits and caused by a large continental ice sheet, moving towards the North. The best evidence of glacial erosion is numerous striated and grooved pavements. (Maria, 1991; unpublished AGOCO report)

The marine and transgressive character of this formation is emphasized by the presence of ferruginous oolites (Bellini and Massa, 1980). El Hawat and Bezan (1998) regarded the Melez Chograne Formation as a transgressive unit reflecting the first major deglaciation event in late Ordovician glacial sequence. The formation is characterised by mass-movement, liquifaction and turbidity flow features (Hallett, 2002).

2.2.2.4 Memouniat Formation (Late Ordovician)

The term was introduced by Massa and Collomb (1960) after Jabal al Memouniat (27° 45’N: 14° 00’E) in the western part of Jabal Gargaf in Fezzan. It is exposed in the Jabal Gargaf, Jabal Ben Ghnema in Fezzan; and Jabal al Awaynat and Jabal Arknu areas in southern Cyrenaica (Banerjee, 1980).

The Memouniat Formation are considered to be the basal transgressive units of the Ordovician-Silurian sedimentary cycle, interrupted by the Melez Chograne glacial episode, and are closely related with the melting of the ice and the marine Tanezzuft transgression. (Maria, 1991; unpublished AGOCO report).

The Memouniat Formation is mainly a sandstone unit, massive, crossbedded, medium to coarse grained, in part conglomeratic and only very slightly consolidated by a kaolinitic cement It has finely bedded fine grained sandstones and very rare micaceous silty shales intercalations (Havlicek and Massa, 1973 in Banerjee, 1980).

Memouniat Formation in Ghadames (Hamada) Basin consists of mainly three depositional facies bounded by time-stratigraphic markers. These facies change in a predictable fashion northwestward from channelized dominated sands to wavy laminated sands (proximal shoreface), and eventually to basinal-offshore bioturbated silt/shale. The sands in the interpreted channels are coarse-grained and relatively thickly bedded than those in the proximal-shoreface. Carbonate cement (calcite) was partially found in the channel-fill sands and proximal shoreface sands which increasing in occurrences in the basinal-offshore bioturbated silt/shale, (Younis, 2013, unpublished MSc. report).

The lower boundary is unconformable with all the older formations. The upper boundary is unconformable with the Silurian Tanezzuft Formation (Klitzsch, 1966). The thickness is generally 328 to 459 (100-140 m) in the type locality (Jabal al Memouniat area), maximum up to 721ft (220 m) and thinning to about 30 m in the Dor el Gussa area (Banerjee, 1980).

2.2.3 Tanezzuft Formation (Early Silurian)

The term Tanezzuft was formally introduced by Desio (1936b) after Wadi Tanezzuft. Klitzsch (1965,1969), described a complete measured section of the Tanezzuft Shales at Takarkhouri about 35 km south of Ghat in the Wadi Tanezzuft, for about 1318ft (402 m) thickness of gray marine shale, partly silty with sandstone lenses, and some thin sandstone beds in the lower part. The Tanezzuft Shales unconformably overlies the Cambrian-Ordovician rocks. The upper boundary is gradual and conformable with the Acacus Sandstone (Banerjee, 1980). Accroding to Goudarzi (1970), the Lower Silurian Tanezzuft Shale is a sequence of green and light to dark gray graptolitic shales having minor beds of fine grained sandstone and siltstone.

The Tanezzuft shales are generally related to deep marine conditions due to a general drowing of the Ghadames Basin after the Taconian unconformity. This was accompanied in the earlier stages by the onset of anoxic conditions (“hot shale” level) and by a general absence of sand inputs (Arduini et al., 2003). It is completely eroded along the northern, east-west trending Nefusa High and along the southern Gargaf High. (Maria, 1991; unpublished AGOCO report).

The thickness of the formation is maximum 1558ft (475 m) south of Ghat, 1318 ft (402 m) in Klitzsch 's type section, about 340 m around Jabal Idinen in the western flank of the

Murzuk Basin, and decreasing towards north in the region of Serdeles and towards the southeast. It is about 524ft (160 m) thick in the northern Dor el Gussa wedging out southward and reappearing north of Mouri Ide with about 100m thickness (Furst and Klitzsch 1963&Klitzsch, 1966 in Banerjee, 1980).

2.2.4 Acacus Sandstone (Formation) (Late Silurian)

The term was introduced by Desio (1936a) after Jabal Acacus near of Ghat, but no type section was designated. Klitzsch (1969) designated a type section (10°28’E:24°32’N), about 50 km south of Ghat at Takarkhouri pass at the base of Jabal Acacus (Mamgain, 1980). Klitzsch’s type section has approximately 1131 ft (345 m)of marine subcontinental sandstone, white, gray and brown, mainly fine grained, thin to thick bedded, quartzitic near the top and shale beds in the lower part. Frequent trace fossils occur on thin bedded sandstones indicating shallow water deposition (Banerjee, 1980). According to Furst and Klitzsch (1963) the Acacus Sandstone is about 656 ft (200 m) thick near Ghat and attains a maximum thickness of about 885ft (270 m) south of Ghat; it pinches out northward toward Serdeles. In northern Dor el Goussa (east flank of the Murzuk basin), the formation has a maximum thickness of 485m, but it pinches out a short distance to the south (Goudarzi 1970).

The Acacus Formation is identified by varying amounts of sandstone alternating with shaly layers. It represents deltaic depositional systems with a progradational trend directed both from SSE to NNW and from E to W. It has been possible to distinguish three areally distinct units (Arduini et al., 2003). The lower boundary with the Tanezzuft Shales described as gradual, whereas The upper boundary is erosive and discordant with the overlying Tadrart Sandstone (Lower Devonian) (Banerjee, 1980).

According to Beicip (1972) The Acacus Formation was subdivided into three lithological parts: A, B, and C which equivalent to Lower Acacus Formation, Middle Acacus Formation and Upper Acacus Formation (Klitzsch et al., 1973). As a matter of fact the Lower Acacus Member, Middle Acacus Member and Upper Acacus Member were not commonly used and considered to be informal term while the Lower Acacus Formation, Middle Acacus Formation and Upper Acacus Formation were commonly used in most Ghadames Basin literatures and considered formal names of the parts of the formation. Accordingly, Lower Acacus Formation, Middle Acacus Formation and Upper Acacus Formation are used to describe the Acacus Formation throughout this research.

2.2.4.1 Lower Acacus Formation

This unit is composed mainly of sandstone (quartzarenites to sublitharenites) which are fine to very fine-grained and characteristically coarsen upward (Teknica, 1995; unpublished AGOCO report). The Lower Acacus is a progradational and cyclic depositional unit reflecting alternating episodes of progradation and transgression inherent in delta construction (Crowder, 1990). The Lower Acacus may be divided into multiple, coarsening upward, progradational cycles which consist of a lower marine shale grade upward into fine grained, well sorted quartzose sandstones and silty shales with occasional sandstones (Cridland, 1991).

2.2.4.2 Middle Acacus Formation

The Middle Acacus is composed predominantly by shales interbedded with rares siltstones and sandstones with mica (Echikh and Suleiman, 1982). The Middle Acacus consists of lower and upper units of transgressive marine shale with an intermediate unit of very silty poorly developed regressive marine sandstones. The Middle Acacus represents a period of relative sea level rise and/or decreased sediment supply with a relatively short, medial phase of stillstand or minor regression (Cridland, 1991).

2.2.4.3 Upper Acacus Formation

The upper Acacus section consists of fine to very fine grained sandstone interbedded with shales. Ferruginuous cement and pyrite nodules are common in the upper part of the unit (Teknica, 1995; unpublished AGOCO report). The Upper Acacus Formation (in the north-west part of the basin) consists of multiple depositional sequences of minor transgressive-regressive marine shales which grade upward into marine-continental sandstones. (Maria, 1991; unpublished AGOCO report).

2.2.5 Devonain

Regionally the Devonian rocks exposed at the northwest flank of the Gargaf arch at Aouinet Ouenine, on the south flank at Shatti valley, on the western and eastern flanks of the Murzuk Basin, in the eastern part of Jabal Nuqay (Eghei), in Jabal Dalma north of Kufra and near the Egyptian border of southern Cyrenaica (Conant and Goudarzi 1964; Goudarzi, 1970), in (Banerjee, 1980). The Lower Devonian strata is missing from the surface outcrops of the Ghadamas Basin along the Gargaf basement 'High' as well as in the nearby subsurface, but a complete succession of Devonian rocks is known from the central part of the basin. (Maria, 1991; unpublished AGOCO report).

The Devonian section reaches a thickness of more than 3000 ft. in the subsurface of both the northern and eastern parts of the Ghadames Basin (Fig. 9). Devonian units onlapped the Gargaf paleohigh creating numerous stratigraphic and structural-stratigraphic traps where many Devonian hydrocarbon accumulations have been discovered (Belhaj, 2000). The Devonian system was subdivided into Tadrart, Ouan Kasa, Aouinet Ouenine and Tahara formations. The limit between these formations is not clear cut because of a great change of facies and thickness. This concern particularly the Tadrart and Ouan kasa formations (Echikh and Suleiman, 1982).

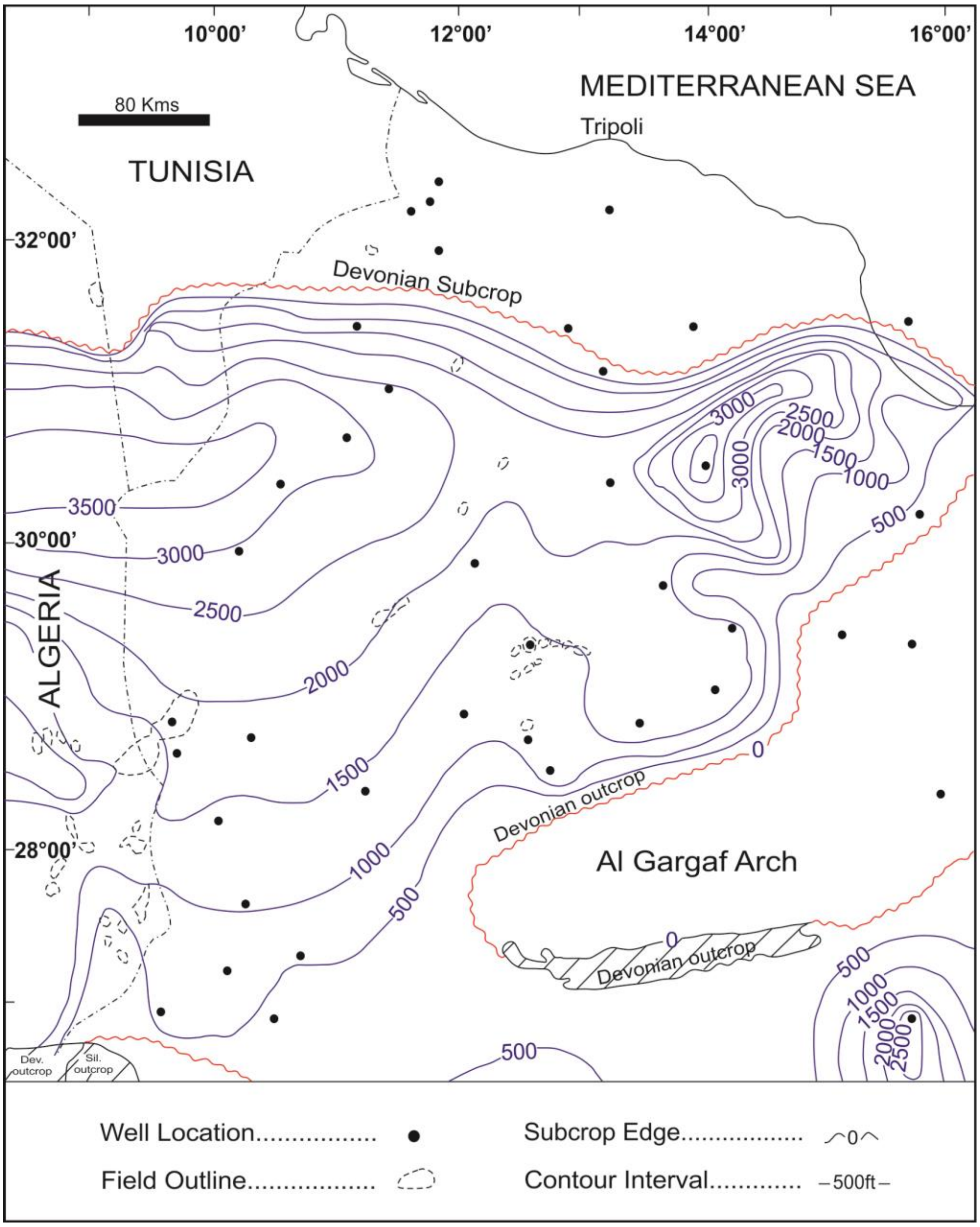


Figure 9. Isopach map of Devonian strata showing the Devonian erosional limit. (after Belhaj, 2000)

2.2.5.1 Tadrart Formation (Early Devonian)

The Tadrart Formation was first described by Burollet, (1960). A type section was designated by Klitzsch, (1965) from the Tadrart Mountains, 35km south of Ghat. At the type locality the Tadrart Formation comprises massive continental to marginally marine sandstones, ferruginous, cross-bedded, with plant remains in the lower part and trace fossils in the upper part (Hallett, 2002). The formation is largely distributed in southern Libya, in Jabal Fezzan, Acacus, Ben Gahnema-Dor el Gussa in the eastern Murzuk basin, Tibesti, Dahone, and in Jabal Hauaisc in the Kufra region (Banerjee, 1980).

The Tadrart Formation represents the first unit to be deposited after the Caledonian Orogeny almost everywhere in the Ghadames Basin. The formation is missing in the Atshan area, to the west of the Gargaf Uplift and in a small area in the northern part of the Ghadames Basin. The formation is also absent due to erosion in the northern and eastern parts of the basin as a result of Hercynian uplift (Belhaj, 2000).

The Tadrart Formation reaches a maximum thickness of about 1148ft (350m) in Jabal Tadrart and wedges out to the north; and in the vicinity of Aouinet Ouenine on the north western flank of Murzuk basin, only about 98ft (30m) is present overlying the lower Silurian Tanezzuft Shale (Burollet, 1963a), in (Goudarzi, 1970).

In the subsurface of the Ghadames Basin the Tadrart Formation is represented by widespread sheet sands cut by numerous sand-filled channels. The thickness averages 426ft (130m) (Belhaj, 2000). The formation is a major oil reservoir in the area from Al Hamra into the Illizi Basin of Algeria (Echikh, 1998) in (Hallett, 2002).

According to Echikh and Suleiman (1982), paleohighs situated in the El Hamada area (Conc. 66) and in El Kebir trend (AA-NC 7A, X1-NC7A, B1-26) where thickness do not exceed 100-150 ft, on the other hand the thickness reaches the maximum in the North western part of Ghadames basin with 300-400 ft. The lower boundary of the Tadrart Formation is unconformable with the underlying Silurian rocks, but the upper boundary is conformable with the Ouan Kasa Formation (Banerjee, 1980).

2.2.5.2 Ouan Kasa Formation (Early-Middle Devonian)

The name Ouan Kasa Formation was first introduced by Borghi and Chiesa (1940). The type locality is at Gour Iduka in the vicinity of Wadi Ouan Kasa, southeast of Ghat where it is made of 141 ft (43 m) of green and grey shales with siltstone intercalations (Tawadros, 2011).

The Ouan Kasa Formation can be subdivided into two members, Lower and Upper. The Lower Member shows substantial facies variation, passing from a very sandy succession in the south to shaly with carbonate layers in the northern part of the Ghadames basin. The Upper Member, in contrast, is of fairly uniform composition throughout the basin, consisting of an alternation of sands, silts and shales. It is of markedly less significance as a producing reservoir (Echikh, 1998).

The Ouan Kasa Formation is widely distributed in southern Libya, in Acacus, Gargaf, Ben Ghnema-Dor el Gussa, Tibesti Mountain, and farther to the east in Kufrah region (Banerjee, 1980). According to Beicip (1972) the formation thickness increases from SE to NW into a maximum thickness zone (up to 900 ft) in the eastern part of the Ghadames Basin. This zone trends SW-NE, then ESE-WNW.

In the subsurface of the Ghadames Basin a sequence of 557ft (170m) thick comprises of fine- to medium-grained sandstones, siltstones and dolomites have been recorded by (Massa and Moreau-Benoit, 1976 in Hallett, 2002)

Along the northeastern flank of Murzuq Basin the Ouan Kasa Formation is best developed in the Dor el Gussa sector where Klitzsch (1963, 1966) records a thickness of 229 to 393ft (70-120m). Collomb *et al.* (1959) estimate the maximum thickness of Ouan Kasa Formation to be around 662ft (202m) in Emi Margi. The lower boundary of the Ouan Kasa Formation is gradual and conformable with the underlying Tadrart Formation, and the upper boundary is unconformable with the overlying Aouinet Ouenine Formation (Mamgain, 1980).

2.2.5.3 Aouinet Ouenine Formation (Middle-Late Devonian)

Rocks of Middle Devonian age were recognised by Borghi in the Aouinet Ouenine area in 1939, but it was Lelubre (1946) who first proposed the name Aouinet Ouenine Formation, and Massa and Collomb (1960) who gave the first systematic description. The type area of the Aouinet Ouenine Formation is located on the northwestern flank of the Al Qarqaf Arch (Gundobin, 1985 in Hallett, 2002).

The Aouinet Ouenine Formation at the type locality consists of interbedded varicolored silty shale, siltstone, and fine-grained sandstone, it reaches a maximum thickness of about 984ft (300 m) (Goudarzi, 1970).

Massa and Moreau-Benoit (1976) raised the rank of the Aouinet Ouenine Formation to that of a group, where they subdivided it into four formations named: Aouinet Ouenine I to IV. The four formations thicken northward in the subsurface of the Ghadames Basin (Tawadros, 2011). According to Furst and Klitzsch (1963) the Aouinet Ouenine Formation attains a thickness of around 984ft (300m) in northern Dor EI Gussa, thinning towards south, with a uniform average thickness of 328 to 492ft (100-150 m) up to Jabal Oieda, further south towards Ehi Loga the formations further thins and locally wedges out (Mamgain, 1980).

The Aouinet Ouenine Formation has been subdivided into three units, from bottom to top: Aouinet Ouenine "A" (A.O.A), Aouinet Ouenine "B" (A.O.B), and Aouinet Ouenine "C" (A.O.C) (Beicip, 1972).

The A.O.A unit is present, in almost, all Ghadames basin, except in the Garian High and the Gargaf uplift. It extends to Awbari Saddle and in the Northern part of Themboka High. The shale in the lower part of this unit named (Emgayet shale) of marine influence. This unit considers one of the main oil targets in the Concession NC7A and the study area (Gullebi Field). The A.O.B. unit has the same distribution as A.O.A. Its thickness ranges from 0 in Garian and Gargaf Highs to the maximum of 800ft (243m) in concessions (NC1, NC2 and NC4).

The A.O.C unit has the same extension as the previous units. The boundary between A.O.B. and A.O.C. is situated at the bottom of radioactive marker constituted by limestones (Tornoceras zone). Its upper limit is indicated by the first micaceous sandstones of Tahara Formation. The thickness has 800 feets in the central part of Ghadames basin (Conc. 90) (Echikh and Suleiman, 1982).

2.2.5.4 Tahara Formation (Late Devonian)

The term ‘Tahara Formation’ was introduced by Massa, Termier and Termier (1974). The type section is given from the CFP Well B1-49 (Massa and Moreau-Benoit, 1976), located on the Wadi Tahara to the South of the Hamada (Banerjee, 1980).

The Tahara Formation is mainly composed of sandstones and siltstones with shale streaks interbedding. Sandstones are fine grained, white or light grey, with siliceous or kaolinitic cement. They can be shaly and grade to siltstones, grey, hard, occasionally glauconitic, Shales are often micaceous (Beicip, 1973).

Spiriferidae and Gastropodos coquina, oolitic ferruginous beds are also known in the Tahara Formation (Beicip, 1972). In D1-66 Brachiopods have been collected in a core cut (Spirifer tornacensis; Orthis michelini, Chonetes sp., Productus sp,, etc..) Undoubtedly the depositional environment was shallow marine (Beicip, 1973).

The Tahara Formation at the study area (Gullebi Field) consists of an interbedded series of sandstones and shales. Average thickness of the Tahara Formation is 137 feet in Gullebi

South and 96 feet at Gullebi North. The Tahara Formation is underlain by shales of the Aouinet Ouenine ‘C’ Formation and overlain by shales of the Carboniferous Mrar Formation (Teknica, 1997).

An isopach map of Tahara Formation in the Ghadames Basin (Fig. 10) was constructed by (El-Rweimi, 1991) is showing that the maximum thickness of the Tahara Formation is about 373ft west of concession NC7A in well A1-90 as this well coincides with the deeper part of the basin. The minimum thickness of this formation is shown in many areas characterized by local to regional elevated areas especially in well B1-70 (106 feet) to the north of the basin, at well NN1-66 (120ft) to the south of the basin and of concession NC7A, at well J1-66 (105 feet) to the east of the basin and concession NC7A. In general, the maximum Tahara thickness in the Ghadames Basin is more than 250 feet, with Tahara section ranges between 110 and 130 feet developed in NC7A (Teknica, 1997). Comparing the isopach map of the Tahara Formation (Fig. 10) and the isopach map of the Devonian strata on (Fig. 9), it is obvious that the Tahara Formation and the other Devonian strata increase in thickness toward the northwest and the northeast of the basin and decreased toward the south and the north where they truncated.

Hassi (1998) recognised a sequence of sixteen shallowing-upwards sequences within the Tahara Formation representing a shelf-shoreface succession in a storm-dominated environment. According to (Bracaccia et al., 1991) the Tahara Formation marks the end of the Devonian and the "tidal flat" conditions were widespread over the whole area.

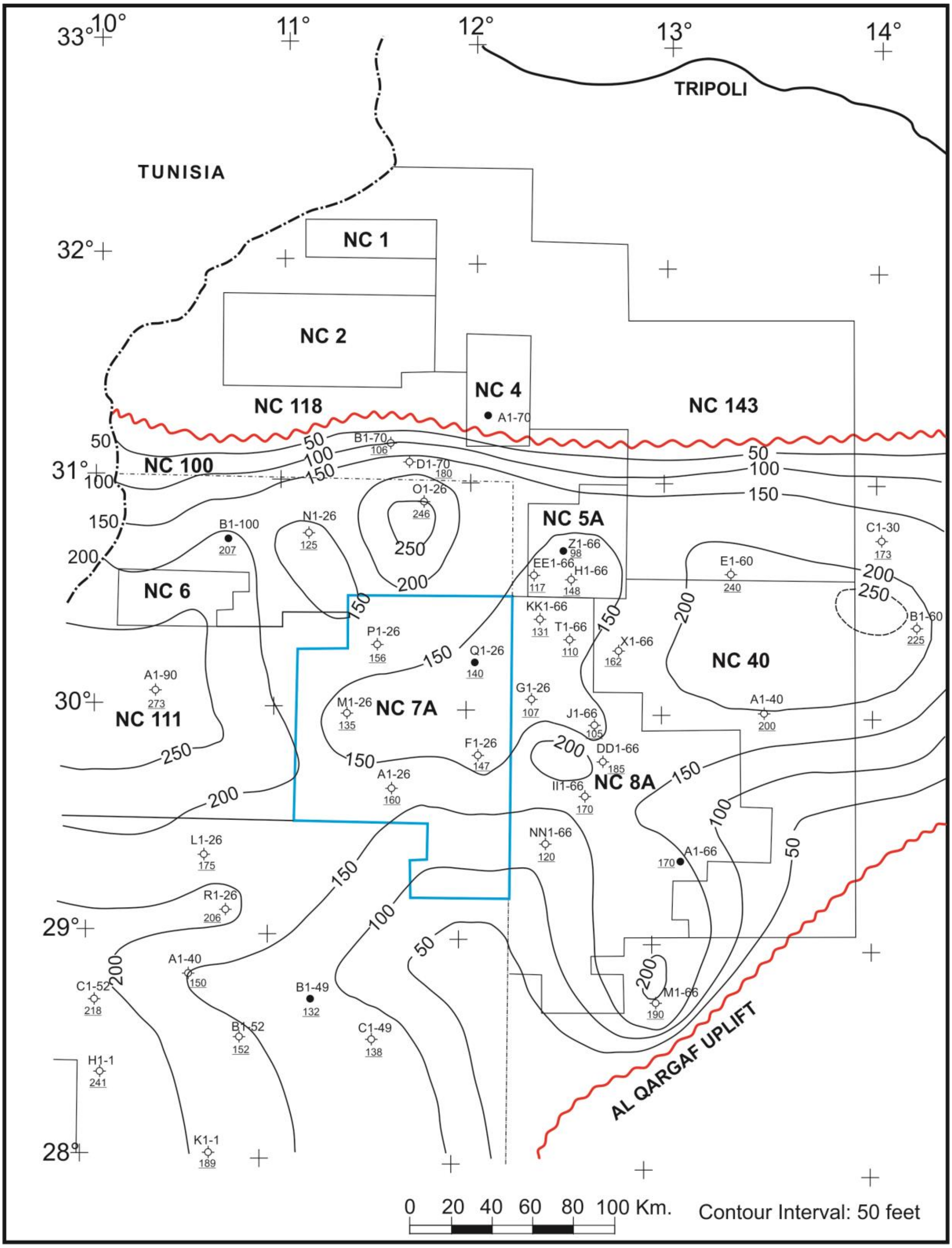


Figure 10. Isopach map of the Tahara Formation in Ghadames (Hamada) Basin. Contour interval: 50 feet. (after El-Rweimi, 1991)

Beicip (1972) suggested a very flat basin during the deposition of the Tahara Formation. During the period of transition from the Devonian to the Carboniferous, that is during the deposition of the Tahara formation, epirogenic oscillations, although weak, affecting the shallow marine basin inherited of the upper Devonian times produced frequent facies changes and stratigraphic gaps, until the wide transgression of the Lower Carboniferous Mrar formation.

The presence within the Tahara Formation of small sedimentary cycles and low-angle, cross stratification indicates tidal effect. The presence of oolitic chamosite indicates wave effects that, together with the presence of bioturbation and burrowing, clearly show normal marine conditions (Elwarfali, 1990 in Maria, 1991; unpublished AGOCO report).

According to Beicip (1973) the Tahara section has been subdivided into three main subdivisions:

- a lower unit, mainly sandstones
- a middle unit, grading upwards from shales to sandstones
- an upper unit, also grading from shales to sandstones

The Tahara Formation consists of coarsening upward sandstone units of different thicknesses, separated by relatively thin shales. The Self Potential (S.P.) and Gamma Ray (GR) log responses indicate considerable variations in the Tahara sandstones, but still there is a degree of similarity existed between the Tahara sections in the various studied wells.

The lower boundary of the Tahara Formation is marked by a conspicuous unconformity (hiatus) (Maria, 1991; unpublished AGOCO report). The Upper boundary overlain unconformably by the Lower Carboniferous Mrar Formation (Banerjee, 1980).

2.2.6 Carboniferous

The Carboniferous rocks were deposited in stable shelf with shallow marine, neritic to littoral environment constantly affected by mild oscillatory movements and eustatic changes in the sea level, resulting in rapid changes, and cyclic (rhythmic) nature of deposition, from transgressive to regressive facies along the marginal parts of the basins (Mamgain, 1980).

The regional north-south trending paleohigh that was effective in the Devonian also affected Carboniferous sedimentation and resulted in a thin Carboniferous section along its axis, dividing the basin into two sub-basins; a larger one to the west and a smaller one to the east (Belhaj, 2000).

Carboniferous strata reach a thickness of more than 5000 ft in the deepest parts of the western Ghadames Basin (Belhaj, 2000). The Carboniferous section is separated from overlying Mesozoic section by the major regional Hercynian unconformity. The main lithostratigraphic units that are represented the Carboniferous section are the Mrar, Assedjefar, Dembaba and Tiguentourine formations.

2.2.6.1 Mrar Formation

The Mrar Formation was first introduced by Lelubre (1948), with its type section in the Qararat el Mrar hills at 28^{o}20' N, 12^{o}15' E in the southern Ghadames Basin. The formation comprises a sequence of alternating silty micaceous shales and micaceous, fine-grained and often ferruginous sandstone with interbedded siltstone and minor limestones (Belhaj, 2000).

Fifteen major sequences have been identified in the Mrar Formation. Most of these sequences are of coarsening upward fashion from shales into fine sandstones, ranging in thickness from 50 to 450ft (15 to 137 m).

The thickness is varying; 2432-2528ft (760 to 790 m) in the Hamada basin, 752 ft (235 m) in the Serdeles area and 1792-1856 ft (560 to 580 m) in the eastern flank of the Murzuk basin (Massa, Termier and Termier 1974 in Banerjee, 1980).

The subsurface thickness of the Mrar Formation reaches more than 3500 ft in the western part of the Ghadames Basin. The thickness distribution indicates that a local sub-basin is also present in the eastern part of the basin (Belhaj, 2000).

According to Whitbread and Kelling (1982) the Mrar Formation was deposited on a slowly subsiding platform and the greater part of the Mrar Formation was deposited in a deltaic setting.

In Dor el Gussa area, the Mrar disconformably overlies the Devonian rocks and marked by its one meter thick basal conglomeratic sandstone bed (Klitzsch 1963), whereas in the subsurface it appears to conformably overlie the Aouinet Ouenine and is conformably overlain by the Assedjefar or unconformably by the Dembaba Formation (Hoen, 1968 in Banerjee, 1980).

2.2.6.2 Assedjefar Formation

The Assedjefar Formation was first defined by Lelubre in 1952, a type locality was subsequently designated by Collomb (1962), 80km west of Awaynat Wanin (Hallett, 2002). Collomb (1962) has described a 623 ft (190 m) thick succession with variable facies from east to west in the type area. In the east the Assedjefar Formation consists of about 328 ft

(100 m) of fine to coarse grained, cross bedded sands and sandstones containing fossil wood with two passages of thinly bedded sandy and silty claystone, followed by a sequence of marly carbonates. In the west within 15 km the facies changes to more or less equal proportions of sandstones and claystones followed by marls and few levels of carbonates (Mamgain, 1980).

The formation exposed in the mountains of Acacus, Gargaf and Jabal Ben Ghnema. In the subsurface; it is found to be present in all the welIs in the northern part of the Murzuk basin. (Banerjee, 1980).

The Assedjefar Formation is present in the subsurface of the southern Ghadames Basin and has been studied in wells A1-49 and B1-49. In this area it is divided into a lower sandy member and an upper dominantly calcareous member with a total thickness of 449 ft (137m) (Bellini and Massa, 1980). It is also about 475 ft (145 m) thick in the Serdeles, about 410-557 ft (125-170 m) in the Hamada basin and about 1377 ft (420 m) in the northeast Murzuk basin (Banerjee, 1980).

The lower boundary of the formation is conformable with the underlying Upper Mrar Formation in the basinal areas. The upper boundary is conformable (gradual) with the overlain Dembaba Formation (Beicip, 1972).

2.2.6.3 Dembaba Formation (Late Carboniferous)

The name was introduced by Lelubre (1952) after Hassi Dembaba well (28°30’N:11°33’E) for the uppermost marine Carboniferous of southern Libya without a description of it is type section (Banerjee, 1980).

Collomb (1962) has provided the general description from the type area, without designating a type section, where the formation consists of about 131 ft (40 m) of gypseous claystone in the lower part with a grayish blue limestone level within the lower 10 metres from the base. The upper part consists of about 196 ft (60 m) of light gray dolomites and highly fossiliferous dolomitic limestone with thin interbeds of claystone (Mamgain, 1980).

The Dembaba Formation exposed in Acacus, Tadrart, Gargaf and Jabal Ben Ghnema-Dor el Gussa mountain areas (Banerjee, 1980). In subsurface the Dembaba formation can be divided into two parts: the lower-Dembaba shales with minor limestones, and localy, anhydrite beds; and the more massive upper-Dembaba limestones (Beicip, 1972).

The formation is about 344-393 ft (105- 120 m) thick in the Hammadah basin, about 60 m in the west flank and 164 ft (50 m) in the east flank of the Murzuk basin. The lower boundary is conformably overlies the Assedjefar, or unconformably the Mrar Formation where Assedjefar Formation is absent. The upper boundary is unconformable with the overlying Tiguentourine Formation (Banerjee, 1980).

The more marine Dembaba Formation rocks represent the stand still of a marine transgression that began with the deposition of the Assedjefar Formation. They are the middle cycle wedge in between the basal transgressive Assedjefar Formation below and the Tiguetourine Formation regressive facies above (Maria, 1991; unpublished AGOCO report).

2.2.6.4 Tiguentourine Formation

Kilian (1931) introduced the term “Continental Post Tassilien Group” for a sequence of continental rocks that overlie the Dembaba Formation. This group is divided by De Lapparent and Lelubre (1948) into three formations from bottm to top: Tiguentourine, Zarzaitine and Taouratine formations (Hallett, 2002).

The type section as designed by B.R.P. geologists is located 60 km WSW of the Tiguentourine spring in the vicinity of Long. 8°35'E and Lat. 27°45'N. In the type area the Tiguentourine Formation consists of about 262 ft (80 m) thick sequence of essentially red and green claystone with some banks of gypsum in the upper 49ft (15m) and thin intercalations of limestones with Ostracods in the middle part (Canaple, 1959 in Mamgain, 1980)

The Tiguentourine Formation marks the last regressive event of Carboniferous sedimentation prior to the culmination of the Hercynian orogeny. These rocks are well developed on the Themboka Arch around Edjele on the Algerian-Libyan border (Hallett,2002).

Chapter (3)

DATA BASE AND METHODOLOGY

3.1 Introduction

In order to understand the strato-structural elements of the Tahara Formation, a package of subsurface data were utilized and which represent a basic requirement to make a scientific research. Some analyzing methods were utilized depending on the requirements of this study and data availability, the assessment of the analyzing data and integrated together helped us to achieve our main objectives. In this chapter we will presented the data base and the methodology applied in this study which intended to be used for assessments at scales ranging from regional to subbasinal.

3.2 Data base

In this study eleven exploration wells drilled in the study area (Gullebi Field, central part of Ghadames Basin) have been selected based on their status and locations in the field, in addition of ten wells from outside the study area (See Table. 1 and Fig. 11 for list and location of the wells). The wireline logs including (Gamma Ray, Spontaneous Potential, Sonic, Neutron-Density and Resistivity Logs) have been recorded for most of the studied wells. These logs were used for facies correlation, determining the position of marker beds and the thickness of facies units and systems tracts sequence boundaries. The gamma ray log was the most useful for delineating facies geometries and depositional relationships.

A total of 635 ft of core samples for Tahara Formation were selected from seven wells. Well A8-NC7A is considered to be a type well based on the core coverage of 150 ft in the Tahara Formation. Some cored section was chosen specifically because it is located in a proven hydrocarbon pool and generally because all core sections present a challenging set of sedimentological properties. Interpretation of depositional environments for the various facies of Tahara Formation was based mainly on the examination of cores and their integration with wireline-logs and thin-section data. Depth of core and wireline logs are given in feet and thickness of internal structures is given in both imperial and metric scales.

Fourty eight (48) core samples were selected from different intervals in sandstone units of Tahara Formation and cut into thin sections by AGOCO Lab Technicians. The thin sections were impregnated with blue resin to facilitate recognition and determination of porosity. Core-porosity-permeability analyses are available for some wells, in addition to well-test results and completion reports. In addition, a limited number of unpublished oil company reports and other published reports and studies.

Table. (1) List of studied wells (See Fig. 11. for wells location).

Well Name	Well Status	K.B (ft)	GL (ft)
HH1-NC7A	Gas	2054	2035
FF1-NC7A	Dry	2098	2036
A13-NC7A	Minor Gas	2076	2036
A9-NC7A	Dry	2085	2046
A10-NC7A	Oil and Gas	2084	2044
A12-NC7A	Dry	2086	2046
A7-NC7A	Gas	2106	2067
A8-NC7A	Oil	2101	2061
A17-NC7A	Dry	2081	2041
A4-26	Gas	2079	2038
A1-26	Oil and Gas	2103	2064
Outside Study Area Wells			
X1-NC7A	Oil and Gas	2033	2016
M1-26	Oil	1993	1933
F1-26	Suspended	2102	2043
PP1-66	Dry	2184	2147
E2-NC8A	Dry	2057	2031
D2-NC7A	Dry	2039	2018
F1-NC7A	Oil and Gas	2088	2054
H1-NC7A	Dry	2044	2023
T3-NC7A	Dry	2057	2039
Y1-NC7A	Oil	1909	1891

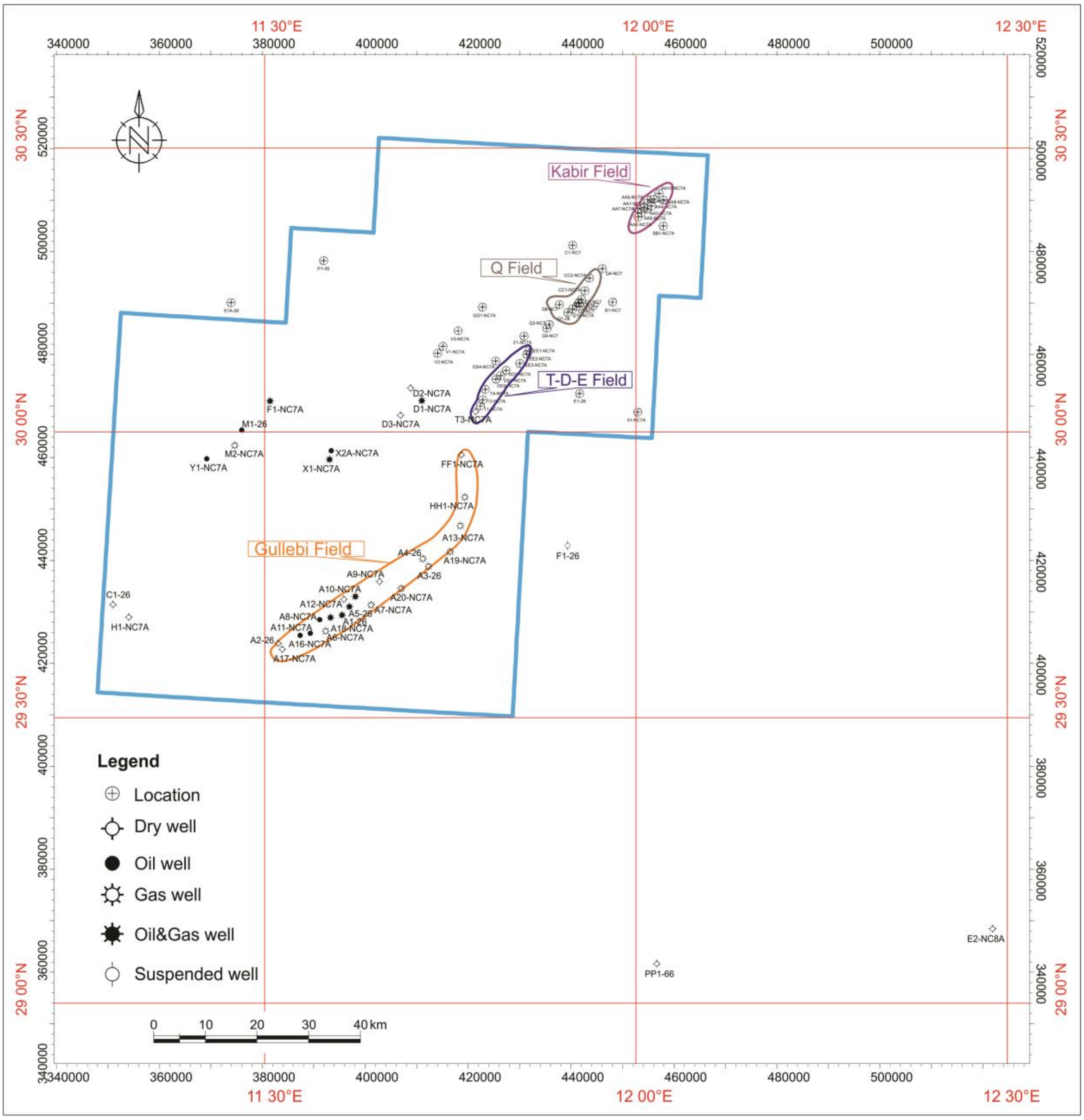


Figure 11. Base map of Concession NC7A, showing location of study area (Gullebi Field) and studied wells.

3.3 Methodology

Four principal methods of study have been used:

1. Subsurface study.
(a) Well log correlation.
(b) Maps construction.
2. Core study.
3. Thin-section study.
4. Petrophysical study.

1. Subsurface study

(a) Well log correlation

Well data are the control points from which regional stratigraphy can be derived and local or regional deviations can be identified that could correlate to structural or stratigraphic changes (Evenick, 2008). Correlation of well logs is a fundamental part of exploration and development programs, where in many basins, interpretation of well log data is the primary method for development of a stratigraphic framework (Campion, 2011). Subsurface well logs (Gamma Ray "GR" and Spontaneous Potential "SP") are used to construct stratigraphic cross sections based on sequence stratigraphic principles. Two cross-sections have been constructed to show the stratigraphic and environmental relationships of the different facies within Tahara Formation.

The first cross-section (Fig. 67 – Encl. 1) is restricted to the study area (Gullebi Field), trending northeast-southwest, at an angle to the proposed regional northwest depositional dip. The second cross-section (Fig. 68 – Encl. 2) is oriented northwest-southeast parallel to the interpreted depositional dip shows gradual facies change of the Tahara Formation from the southeast sediments source area to the northwest marginal basin area.

In order to start reconstruction of stratigraphic cross section and making lithostratigraphic correlation work, a marker bed had to be identified on every single well log. In this study, the lower Mrar Marker bed is found in every well without exception and its readily identified log character. It was formed after the Tahara fill, thus is an ideal datum to demonstrate the Tahara topography on cross sections.

Well log data were supported by the Arabian Gulf Oil Company (AGOCO)- Benghazi , Libya . The relevant wells are marked on the location map (see table. 1 for list and Fig .11 for location) and are widely distributed throughout the study area.

(b) Map construction

b-1 Isopach maps

The isopach map constitutes one of the basic records for any palaeogeographic interpretation. This map aids in illustrating thickness variations, trends, dimensions and shape of a given unit or formation. Also some other characteristics of basin features like buried ridges, subsidence areas and deep basin areas to basin flank can be stratigraphically detected. To schematically represent the thickness variation and trends of the Tahara units, and also to support the depositional environment interpretation, total isopach map was generated on the basis of the log correlation of 49 wells in the study area. Two isopach maps were generated for the upper and lower sandstone units using well data of 18 wells to illustrate sandstone morphology which may reflect the patterns of the depositional environment. Also ispocah map for the entire Tahara Formation in order to assess basic ideas of the depositional history in the study area.

b-2 Structure maps

Tahara Formation tops were picked in 49 wells and used to create subsurface structure map. The main benefit of creating structure map is to show the configuration of stratigraphic surface of the Tahara Formation, which allowing recognizing the highs and lows in the study area, regional dip and any structure features (faults, folds, etc..). The paleo-drainage system in the study area can be recognized from this type of maps.

b-3 Log facies maps

Log facies can be defined as ".. the set of 1og responses which characterize a bed or unit and permits it to be distinguished from the others.." (Serra , 1985 ; Serra , 1989) .
Integration of the log shapes with isopach maps showing the geometry of each sandstone unit, makes it possible to interpret depositional environments (Bulling and Breyer , 1989 in Elfigih, 1991). Two logfacies map constructed for the upper and the lower sandstone units of the Tahara Formation in the study area. Showing the trend of facies characteristic change for each unit.

2. Core study

Cores data was provided by the Arabian Gulf Oil Company (AGOCO)-Benghazi, Libya, a total of 635ft of core sections for 7 wells, 3 of these wells are located outside the study area and the others distributed in the study area (Fig. 12). The core data were calibrated with the wireline logs and described in detail, establishing a lithofacies framework. Recomended core description sheet format (Fig. 13) was used to fully define the cored intervals in terms of their lithology, lithofacies, grain size, sedimentary structures, porosity, DST intervals and oil stain. All core samples and their internal sedimentary structures were photographed. Grain size was visually measured using a hand lens. Cores recovery was in general good in most of the cored wells. However, some cored intervals in few wells were partially or totally mist.

3. Thin section study

On the basis of core analyses, a total of 48 thin sections from seven (7) wells were prepared in the Geological Lab at Arabian Gulf Oil Company (AGOCO)-Benghazi, Libya. Only 26 selected thin sections were analysed petrographically (Tables 2-4). The thin sections were impregnated with blue resin to facilitate recognition and determination of porosity. Detailed petrography was carried-out using polarizing microscope (MICROS Edelweiss Mcp300-Micros-AUSTRIA), supported by thin section photomicrographs to illustrate key features. Full thin section descriptions were undertaken with an emphasis on factors affecting reservoir properties, such as porosity, textural parameters, sedimentary structures and mineralogical composition, as well as the post-depositional diagenetic features. Percentages of constituents within the sections were determined using point counting of at least 300 grains per thin section. Thin section examination has to be used to aid in the construction of the depositional environment model of Tahara Formation.

4. Petrophysical study

In this study some available petrophysical data for fourteen (14) wells (conducted by AGOCO Lab, Benghazi, Libya) including porosity-permeability variation, oil-water saturation and grain density for some intervals of Tahara Formation will be discussed in next chapters.

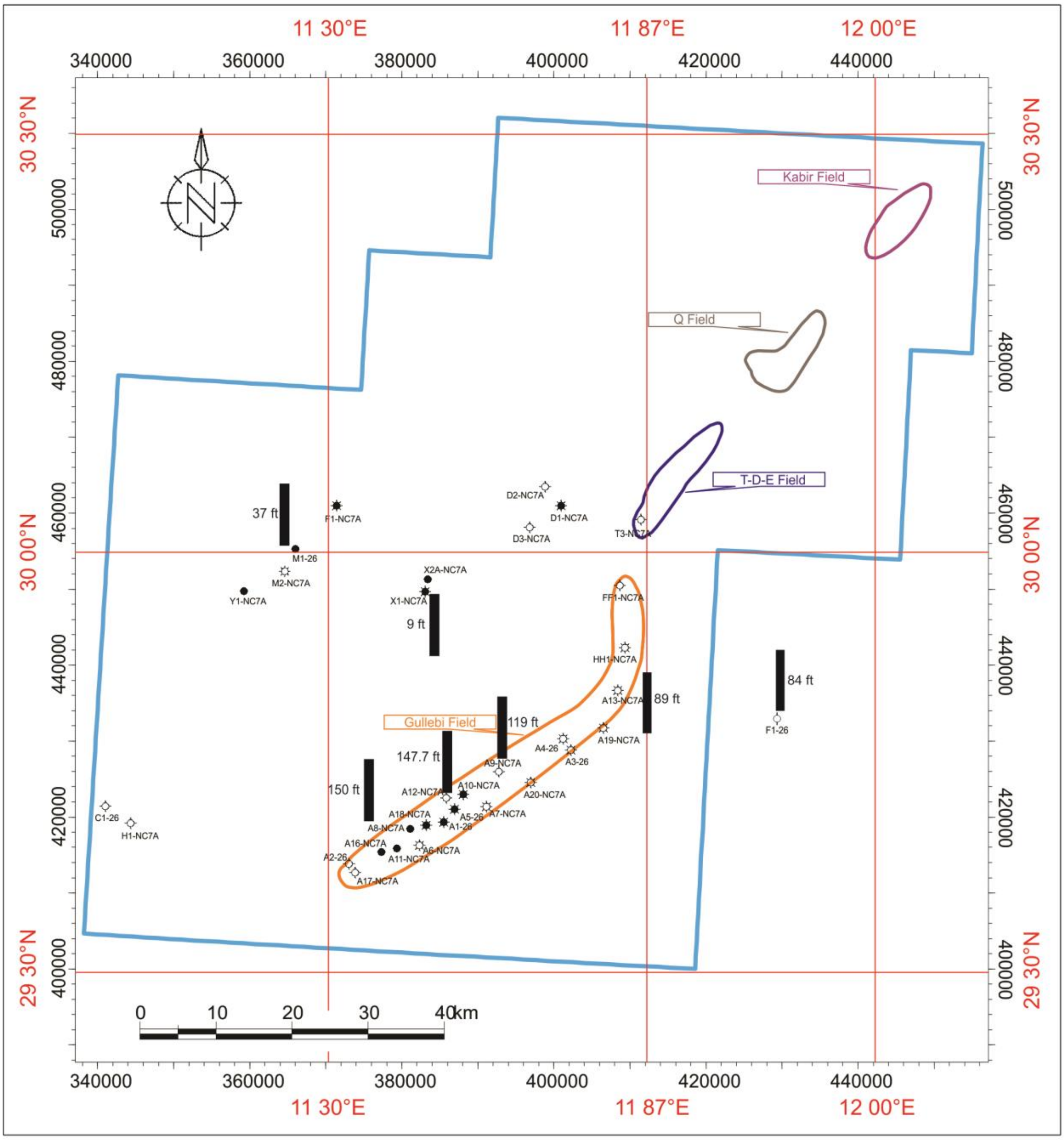


Figure 12. Location map of concession NC7A, showing cores (black columns) cut in Tahara Formation, were used in this study.

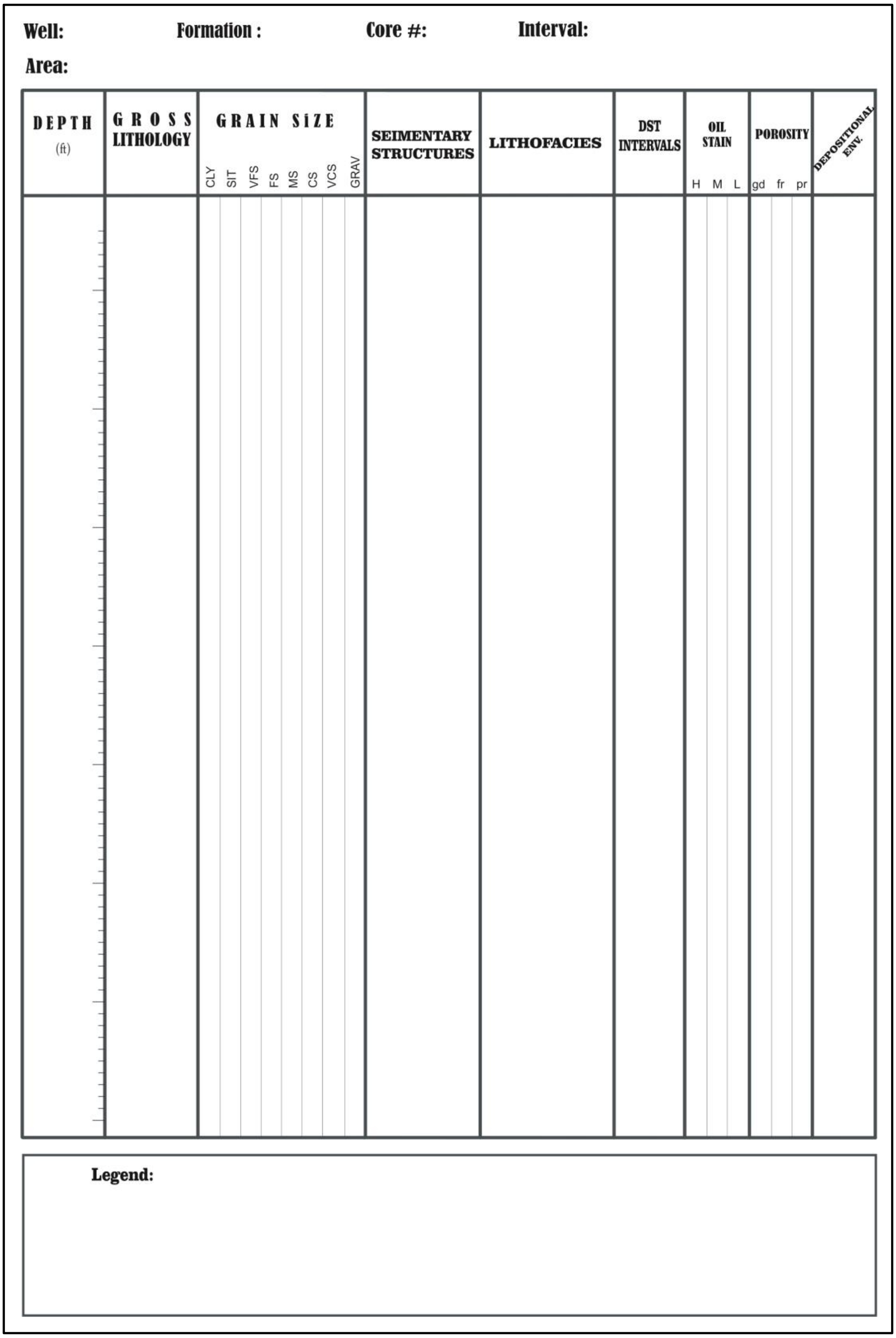


Figure 13. Recommended core description sheet format to be used for describing cored intervals in studied wells.

(Chapter 4)

Lithofacies Analysis of Tahara Formation

Based on continuous cores and electrical log data (mainly GR. Log) from type well (A8-NC7A) and supplemented by cores and wireline logs from other wells (A9-NC7A, A12-NC7A, A13-NC7A, X1-NC7A, M1-26, F1-26, HH1-NC7A, FF1-NC7A, A17-NC7A, A4-26. A1-26, A7-NC7A, PP1-66, E2-NC8A) (Fig. 14) seven lithofacies have been recognized in the Tahara Formation. Each lithofacies is defined on the basis of lithology, fossil contents and sedimentary structures. The identified lithofacies can be described using the type well A8-NC7A as following:

4.1 Lithofacies (1) Dark grey micaceous bioturbated shale

This lithfacies, represented by the cored interval from 5838' to 5850' in the type well A8-NC7A (App.I.1), it is also present in the wells A9-NC7A, A12-NC7A and A13-NC7A (App.I.4, App.I.7 and App.I.11). This lithofacies consists mainly of thick sequence of dark grey micaceous bioturbated shale, which is occasionally with lenticular sand lenses (App.I.3). It becomes very bioturbated, structureless (massive) as in well A8-NC7A at (5848.6-5848.9ft) C#5 (Fig. 15A). This lithofacies has a generally gradational contact with the upper deltaic sandstone deposits.

In the area of A9-NC7A, a similar lithofacies of about 12ft, consist of finely laminated compacted marine shale with some enclosed streaks of bioturbated silty sandstone has been detected (Fig. 15B and App.I.4). A repeated cycle of this lithofacies has been reported within the same area, constitute of about 30ft of black finely laminated shale (App.I.5 and App.I.6).
The predominance of dark color shale representing high content of carbonaceous material and anoxic condition. Also changes of color from dark gray shale to light silty shale imply changes of sedimentation rate from slow to fast. With the presence of lenticular sand lenses we suggest that lithofacies (1) was probably deposited in quiet water basinal (offshore marine) environment.

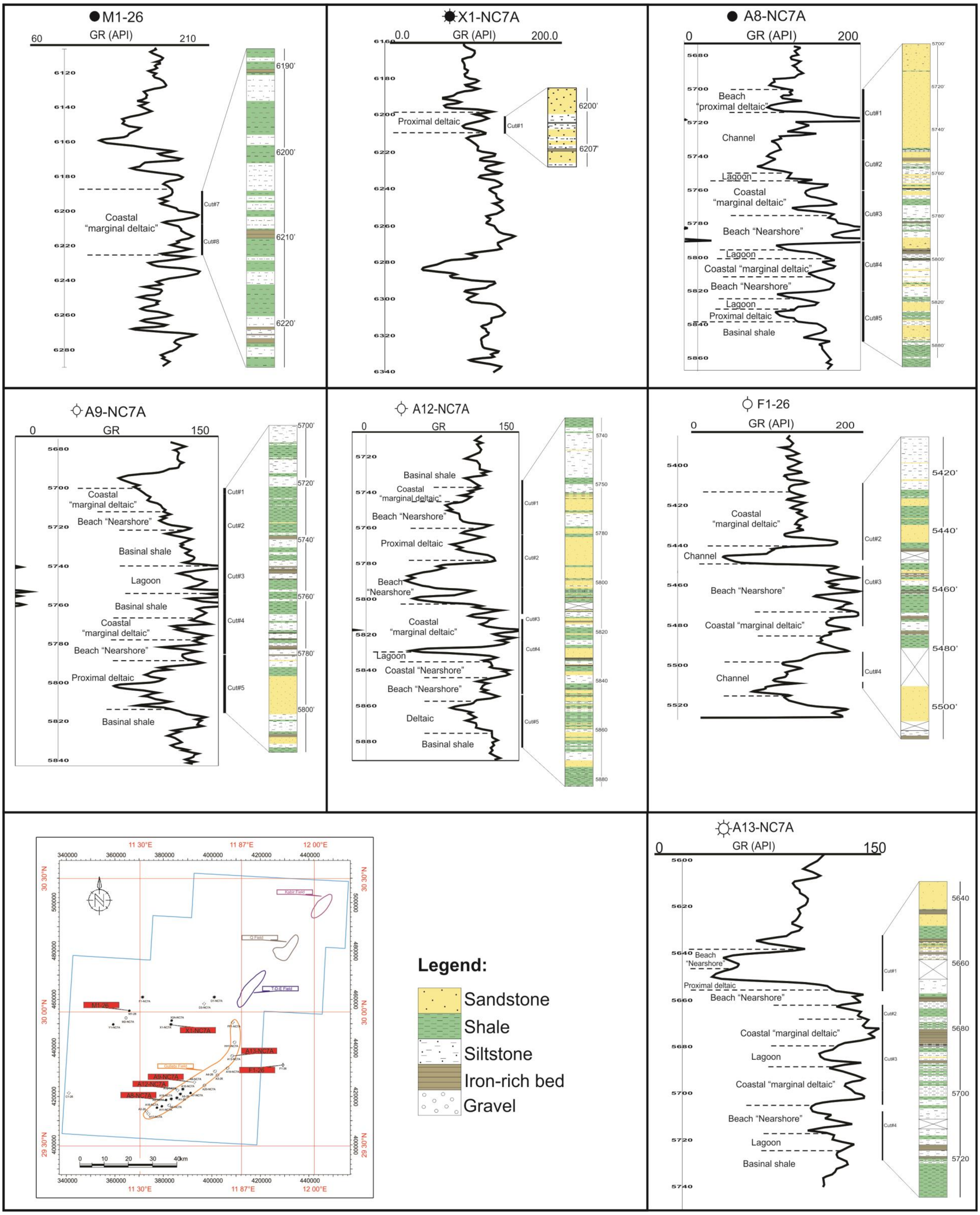


Figure 14. Gamma Ray (GR) log response of the studied seven (7) wells, showing the cored intervals and the different lithofacies of Tahara Formation, ConcessionNC7A.

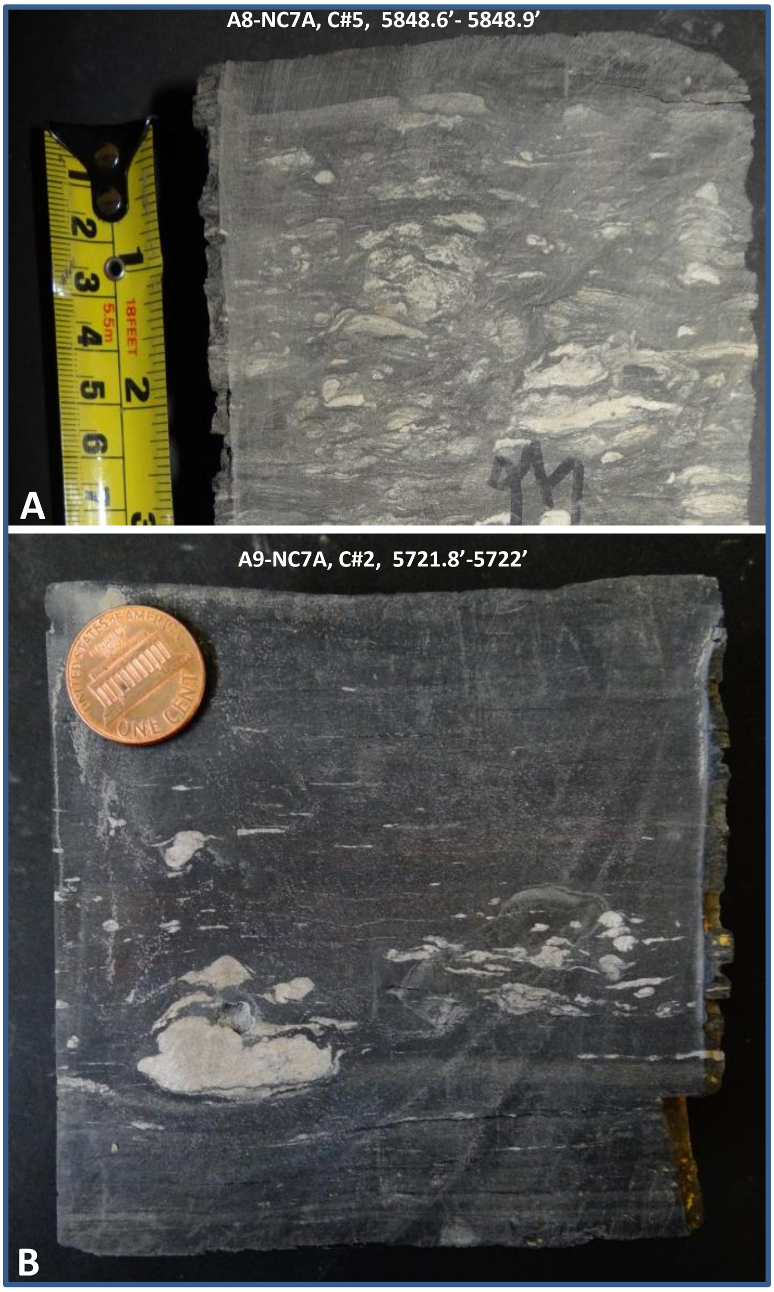


Figure 15. Slabbed core sample of lithofacies (1) of Tahara Formation in wells (A8-NC7A & A9-NC7A), concession NC7A, Ghadames Basin showing **A.** Dark gray, micaceous, bioturbated shale, **B.** Compacted, finely laminated black marine shale with some silty sandstone inclusions.

4.2 Lithofacies (2) Parallel laminated silty sandstone and silty shale

This lithofacies, represented by the cored interval from 5830.9 to 5838ft in the type well A8-NC7A (App.I.1), it is also present in the wells A9-NC7A and A12-NC7A (App.I.4 and App.I.7). It consists mainly of a sequence of dark–light gray, very fine to fine, well sorted, subrounded-rounded, micaceous sandstone, parallel laminated with carbonaceous materials (Fig. 16A) and silty shale lamination with fossil remains at places, clay clasts and bioturbation restricted in the upper part of the lithofacies in well A8-NC7A (App.I.3). In the area of A9-NC7A well, ripple marks, hummocky cross stratification and low angle planar lamination has been observed within this lithofacies (Figs. 16B, C and App.I.6). In the well A12-NC7A it is consist mainly of highly bioturbated sandstone and silty sandstone in the lower part and laminated silty sandstone occasionally silty shale in the upper part, the sandstone is very fine-fine grained (App.I.9), vertical skolithos burrows about 6cm long has been observed (Fig. 16D).

Similar lithofacies observed in the far northwest of the Gullebi Field, in the area of well X1-NC7A, represented by the cored interval from 6198’-6206’ (App.I.18), consists of sequence of about 9 feet of interbedded laminated siltstone and sandstone with some shale laminae, bioturbated and with iron-rich streaks at places. The sandstone is light brown, occasionally light gray, very fine, well sorted, subrounded-rounded, massive, with oil stained in the upper 3 feet (App.I.19). Nodular structures in the iron rich bed and some cross laminations of siltstone were also observed (Figs.17A-D)

This lithofacies has a sharp contact with the upper lithofacies demonstrated by a funnel shape on Gamma ray log, except in F1-26 well, demonstrated by finning upward nature (bell shape), and we believe it representing channel deposits in this particular area (see Fig. 14). The parallel laminations defining low flow regime along with the carbonaceous materials indicate proximity to shore line, the presence of skolithos vertical burrows with the rippled sandstone and hummocky cross stratification suggested wavy dominated shallow shelf, also the presence of iron-rich bands or streaks gives indication on oxic condition, all these features give indication that this lithofacies has been deposited in nearshore/deltaic complex depositional environment.

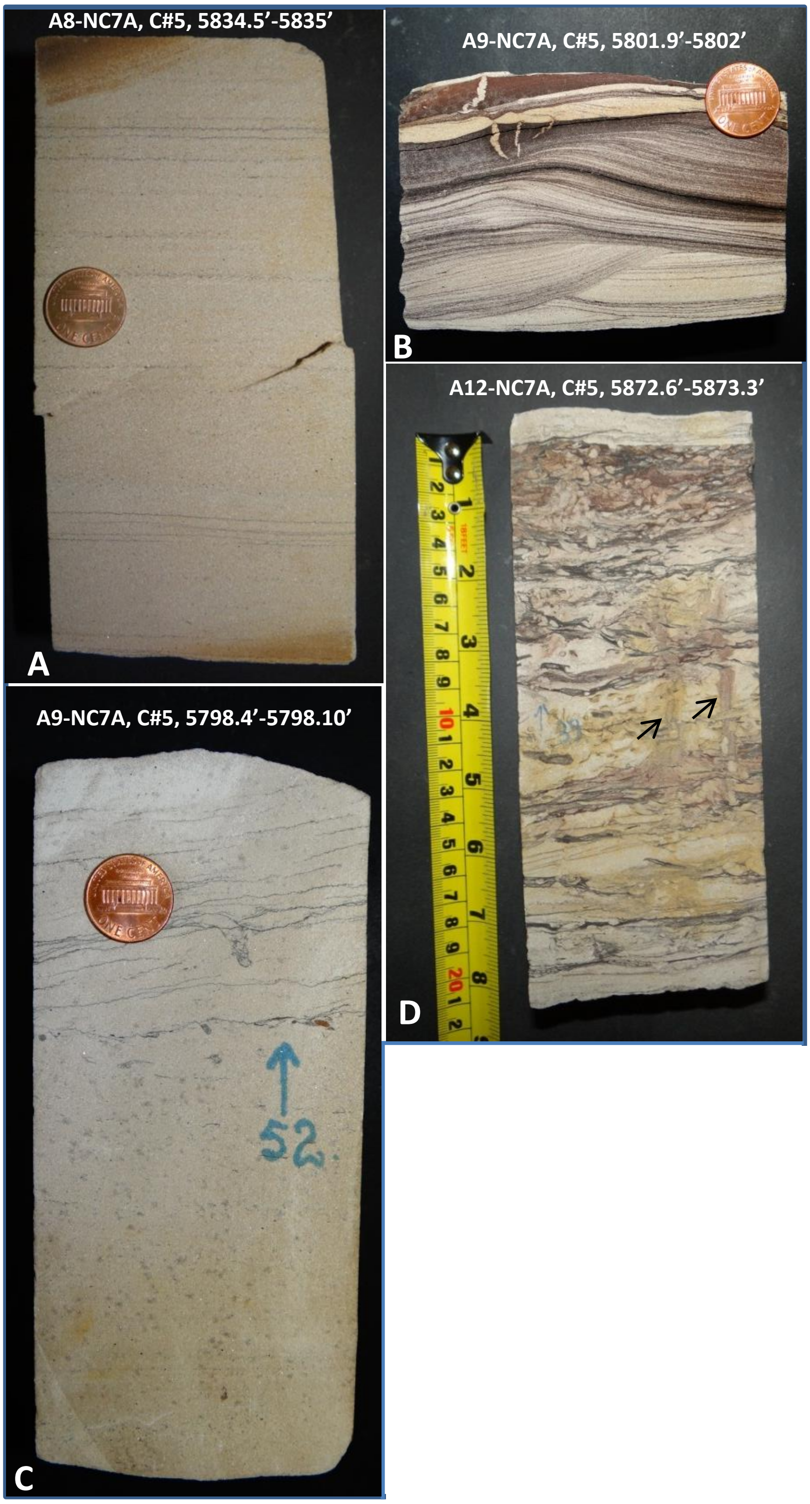


Figure 16. Slabbed core sample of lithofacies (2) in Tahara Formation, in wells (A8-NC7A, A9-NC7A, A12-NC7A and F1-26), concession NC7A, Ghadames Basin showing, **A.** Parallel laminated sandstone with carbonaceous materials, **B.** Hummocky cross stratification, **C.** Laminated sandstone with ripple and carbonaceous materials, **D.** Sandstone with vertical skolithos burrows (arrows).

.

Figure 17. Core sample of lithofacies (2) in Tahara Formation, in well (X1-NC7A) , concession NC7A, Ghadames Basin showing, **A.** Laminated silty sandstone with shale laminae, bioturbation at the lower part, **B.** Bioturbated silty sandstone, **C.** Iron-rich shale with mud clasts, **D.** Oil stained massive sandstone.

4.3 Lithofacies (3) Varicoloured silty shale and bioturbated iron-rich shale

This lithofacies, represented by the cored interval from 5824.5’ to 5830.9’ in the type well A8-NC7A, repeatative cycles observed at the cored intervals from 5795.6’ to 5800.8’ and 5750.3’ to 5754.3’ (App.I.1). This lithofacies also observed in the area of wells A9-NC7A, A12-NC7A and A13-NC7A with a repeatative cycle also detected in A13-NC7A (App.I.4, App.I.7 and App.I.10).

This lithofacies consist of varicoloured silty shale and horizontaly laminated silty sandstone with nodular iron-rich structures and clay clasts, bioturbated in the lower part, a hummocky cross stratification was observed in the laminated silty sandstone (App.I.3 and App.I.12), vertical burrows filled with light-dark gray silty sandstone were also observed (Fig. 18A-D).

The iron-rich nodular structures may be come down from rivers into lagoon which provides reducing condition favorite for their deposition under some influences of rivers and terrigenous sedimentation.

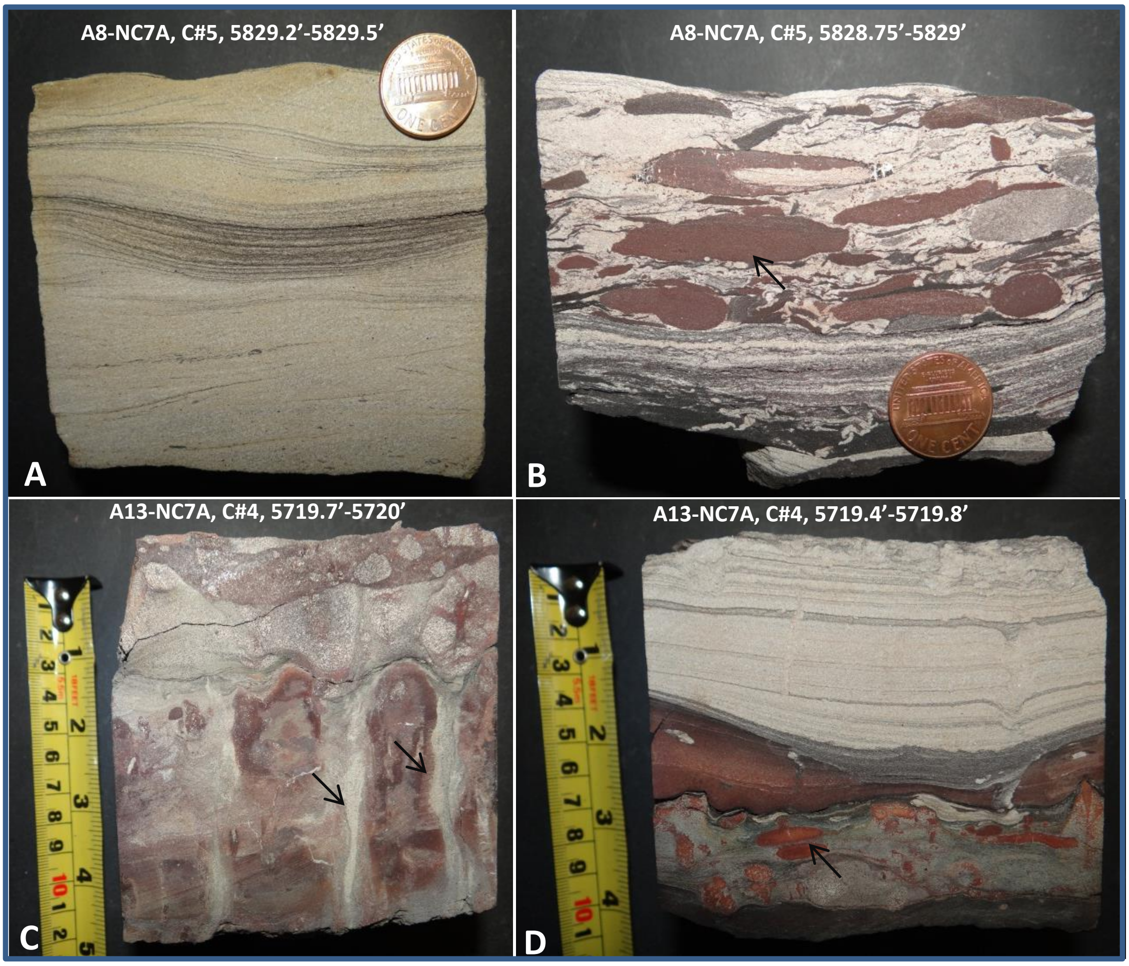


Figure 18. Slabbed core sample of lithofacies (3) in Tahara Formation, in wells (A8-NC7A & A13-NC7A), concession NC7A, Ghadames Basin showing, **A.** Hummocky cross lamination, **B.** Parallel laminated silty sandstone and silty shale with iron-rich nodular structures (arrow), **C.** Iron-rich shale with vertical burrows filled with silty sandstone (arrows), **D.** Parallel laminated silty sandstone with iron-rich nodular structures at the base (arrow).

4.4 Lithofacies (4) Bioturbated sand and shale

This lithofacies, represented by the cored interval from 5811.3’ to 5823.5’ in the type well A8-NC7A with repeatative cycle from 5775’-5795.6’ (App.I.1). This lithofacies consists of fine to very fine, light gray, micaceous sandstone, flaser laminated (Fig. 19A), occasionally structureless (App.I.2 App.I.3), with intensively bioturbated sand and shale (Fig. 19B), occasionally with ripples lamination, clay clasts, and some streaks of dark reddish iron-rich shale . This lithofacies also has been observed in the areas of A9-NC7A, A12-NC7A, A13-NC7A and F1-26 wells (App.I.4, App.I.7, App.I.10 and App.I.13) with repeatative cycles detected in A9-NC7A and A12-NC7A wells.

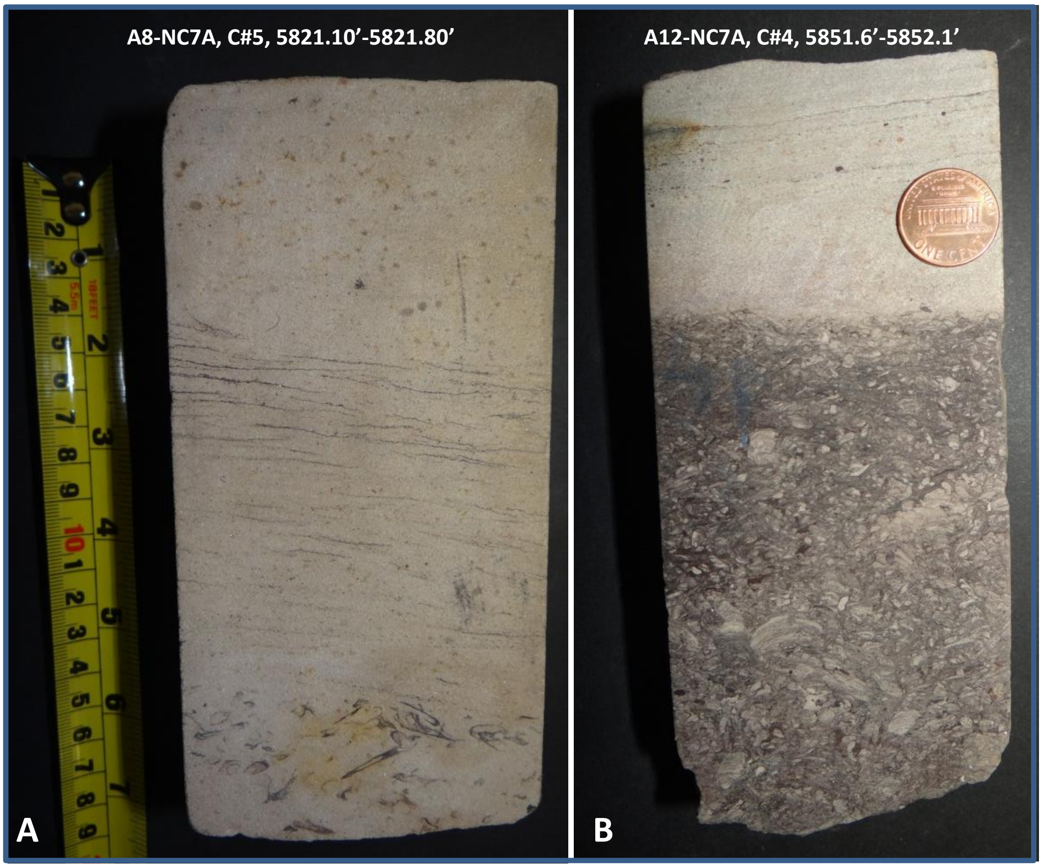


Figure 19. Slabbed core sample of lithofacies (4) in Tahara Formation, in wells (A8-NC7A&A12-NC7A), concession NC7A, Ghadames Basin showing, **A.** Flaser laminated sandstone, **B.** Parallel laminated sandstone (Top), and bioturbated shale (Bottom).

To the northeast from the type well, in the A9-NC7A well area, this lithofacies contains some iron-rich shale streaks (Fig. 20A) reaches to 1 foot in thickness (App.I.6), further north in the area of A13-NC7A well, this lithofacies consists of completely bioturbated (Fig. 20B), wavy laminated silty sandstone and shale (App.I.12), with clay clasts, occasionally parallel laminated or structureless silty sandstone streaks.

However; the presence of the flaser bedding or lamination implies that both sand and mud were available under alternating current activities (Reineck and Singh, 1980), thus we can conclude that this lithofacies was deposited in an area close to the coast, may be beach (nearshore) environment. Moreover the presence of iron-rich shale also give a clue for its deposition some distance from land (beach zone)

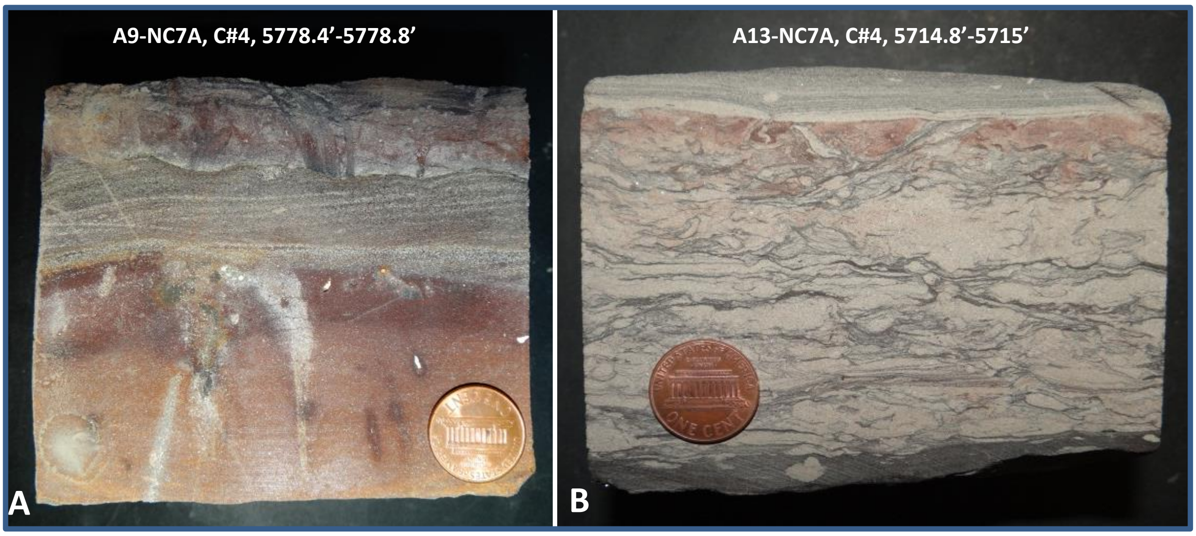


Figure 20. Slabbed core sample of lithofacies (4) in Tahara Formation, in wells (A9-NC7A and A13-NC7A), concession NC7A, Ghadames Basin showing, **A.** Iron-rich shale with vertical burrows, **B.** Intensively bioturbated sandstone.

4.5 Lithofacies (5) Interlaminated shale and silty sandstone

This lithofacies is represented by the cored interval from 5800.8' to 5811.3' in the type well A8-NC7A with repeatative cycle from 5754.3'-5775' (App.I.1). It consists of sequence of interlaminated shale and silty sandstone with some streaks of very fine-fine, light gray and micaceous sandstone, burrows are rarely dominant, occasionally with cross laminated at places (App.I.2 and App.I.3) (Figs. 21A-D). To the northeast, in the areas of A9-NC7A and

A12-NC7A wells, the same lithofacies represented by the cored intervals from 5766.4’ to 5777.9’ and 5835’ to 5843.11’ (App.I.4 and App.I.7) was recovered (App.I.6 and App.I.9), where the lower part is more shaley with minimal bioturbation. Repeatative cycles of this lithofacies were observed in the cored sections of well A9-NC7A (App.I.4 and App.I.5) and in well A12-NC7A (App.I.7 and App.I.8).

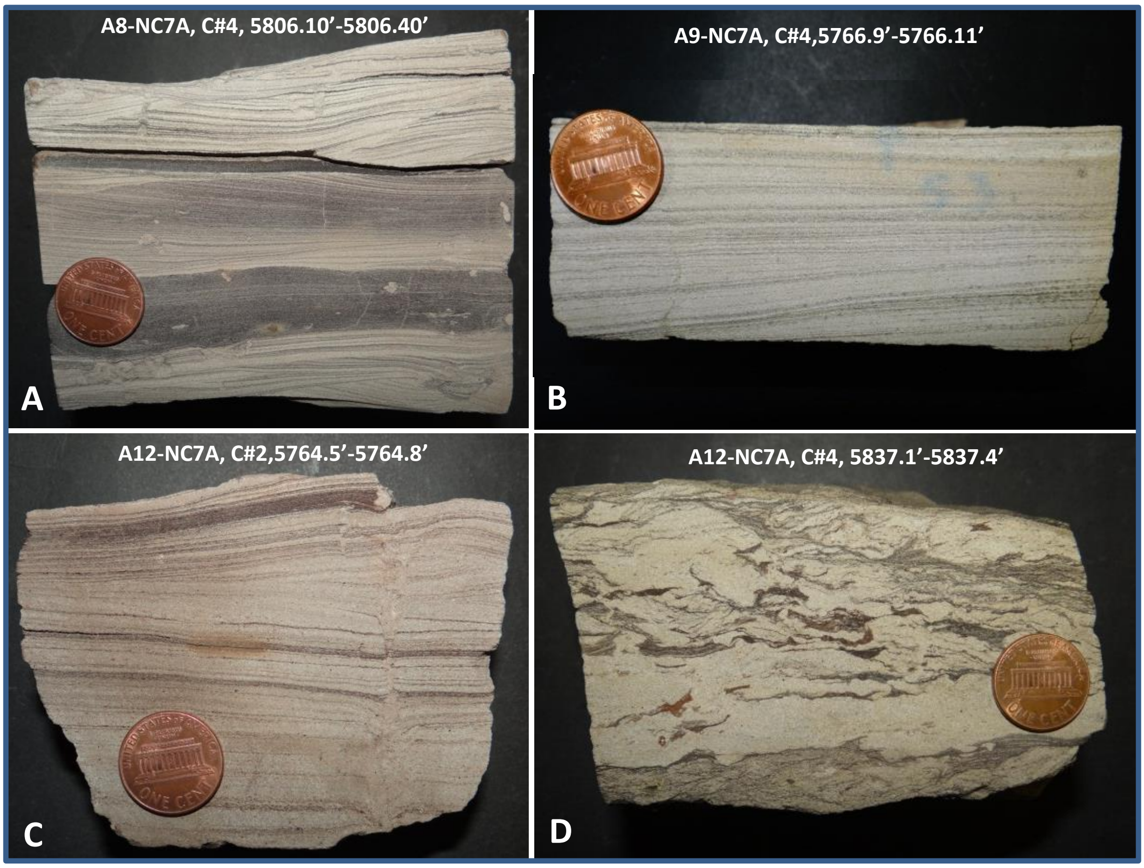


Figure 21. Slabbed core sample of lithofacies (5) in Tahara Formation, in wells (A8-NC7A, A9-NC7A and A12-NC7A), concession NC7A, Ghadames Basin showing, **A.** Alternating laminated and cross laminated silty sandstone, **B.** Horizontal laminated sandstone **C.** Cross laminated sandstone with some vertical burrows (skolithos), **D.** Bioturbated sandstone with clay clasts.

This lithofacies is well developed further northeast in the area of A13-NC7A, where it covers most of the formation thickness, in a repeatative cycles observed to directly overlain the lithofacies (3), with net thickness about 23.8 feet (App.I.10, App.I.11, App.I.12 and Figs. 22A-B).

Similar lithofacies has been observed, and represented by the cored interval from 5437' to 5485' with repeatative cycle from 5413' to 5440' in the well F1-26 (App.I.13), see detailed description sheet (App.I.14 and App.I.15), see (Fig. 22C).

In the area of M1-26 in the far northwest from the Gullebi Field, we observed a sequence of about 38 feet thickness represented by the cored interval from 6187' to 6225' (App.I.16), this sequence consist of laminated silty sandstone and carbonaceous shale with some streaks of silty sandstone and iron-rich beds, occasionaly bioturbated (App.I.17) (Fig. 22D-E). The core cuttings were in bad condition and some parts were missing, so the interpretion of this interval may not be correct, but we tend to attribute this interval to the lithofacies (5).

The presence of carbonaceous and rich ironstone materials beside the highly bioturbated beds give indication that this lithofacies were deposited on an area close to the continent may be coastal plain (coastal "nearshore" environment).

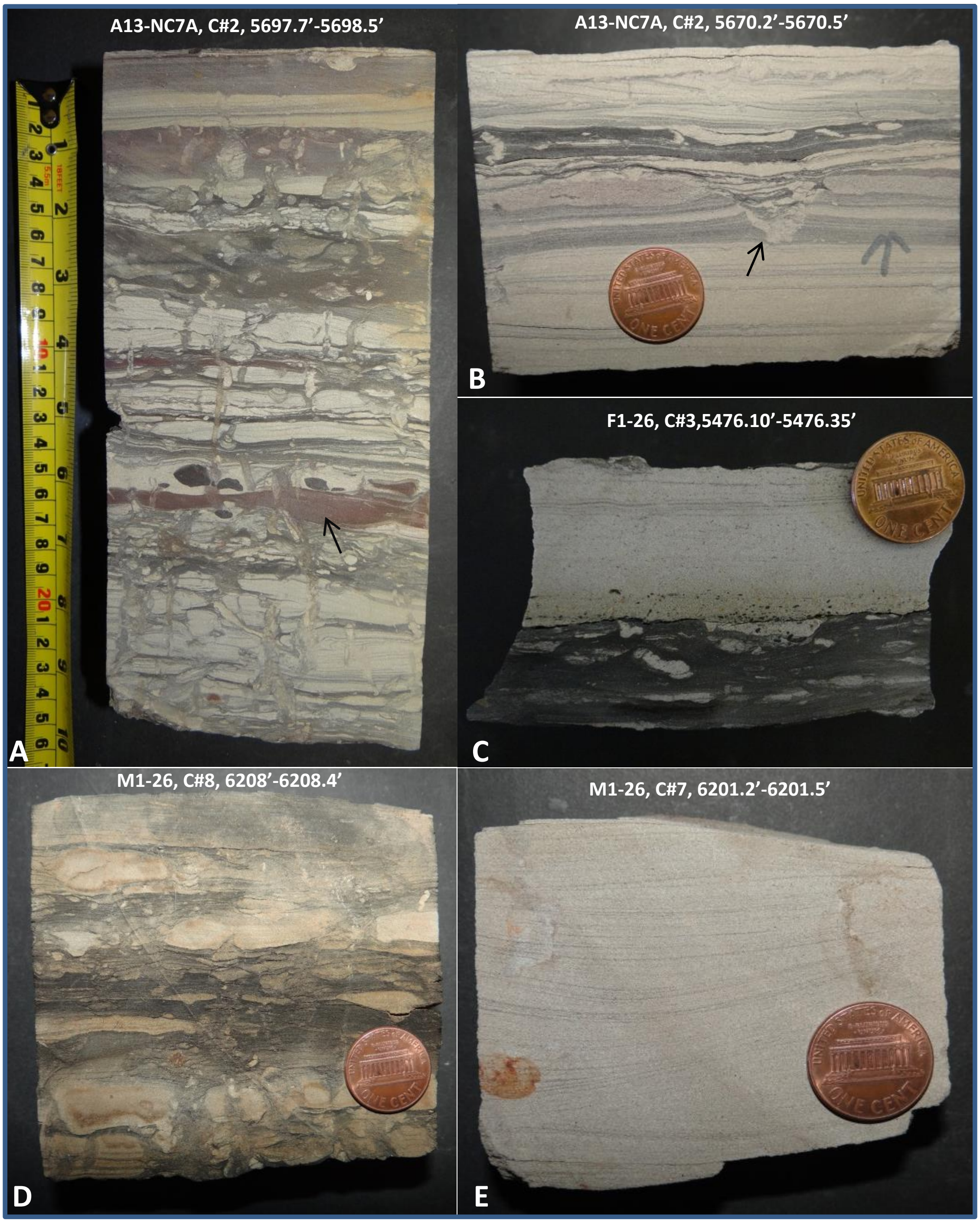


Figure 22. Slabbed core sample of lithofacies (5) in Tahara Formation, in wells (A13-NC7A, F1-26 and M1-26), concession NC7A, Ghadames Basin showing, **A.** Burrowed laminated silty sandstone with clay clasts and sideritic laminae (arrow), **B.** Laminated silty sandstone at the base, bioturbation destroyed horizontal laminae at the top (arrow), **C.** Laminated silty sandstone and shale with carbonaceous material, **D.** Bioturbated silty sandstone and carbonaceous shale of coastal deposits. **E.** Cross laminated silty sandstone.

4.6 Lithofacies (6) Massive sandstone and gravel

This lithofacies, represented by the cored interval 5712.9’ to 5750.3’ in the type well A8-NC7A (App.I.1). It has an erosional contact with the lower lagoonal deposits, the lower most part consists of iron-rich beds and coarse materials (Fig. 23A), the cored interval from 5712.9’-5748.3’ consists of light gray-gray, fine grained, well sorted, subangular-subrounded, micaceous, structureless (massive) to rippled laminated sandstone with clay clasts (App.I.2), see (Fig. 23B).

Further to the far northeast, in well F1-26 similar lithofacies represented by the cored interval from 5498’-5516’ has been observed (App.I.13). It consists of very fine to fine, subangular-subrounded, well sorted, micacous, massive sandstone with coarse materials, with some shale laminae and mud clasts (App.I.15). Repeatative cycle of almost 6 feet was also recovered in core#3 of well F1-26 (App.I.14), see (Figs. 24A-B).

The presence of the coarse materials (lag deposits) and ripple lamination indicating on active river channel.

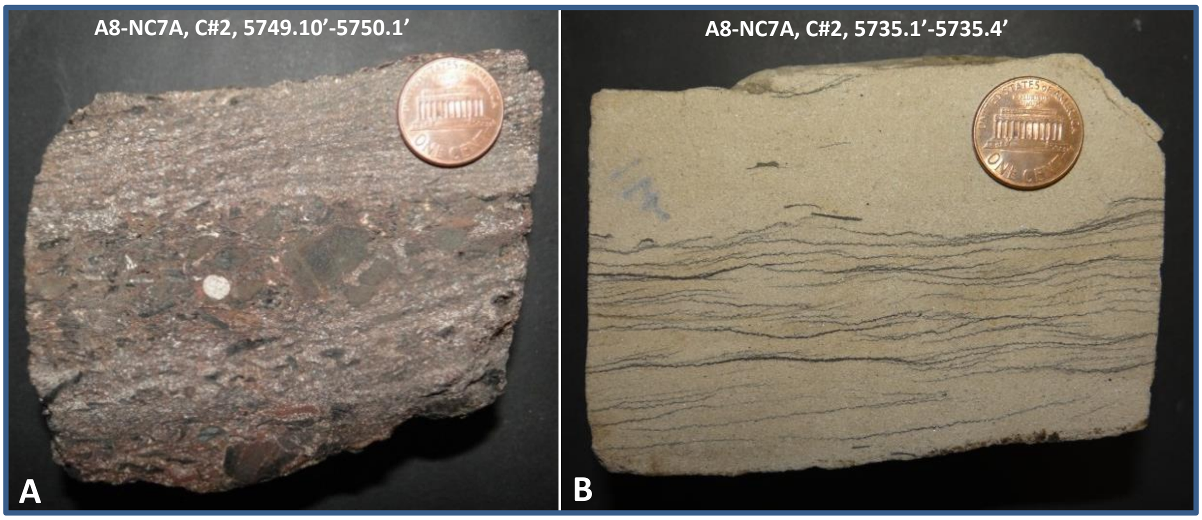


Figure 23. Slabbed core sample of lithofacies (6) in Tahara Formation, in well (A8-NC7A), concession NC7A, Ghadames Basin showing**, A.** Coarse materials (gravel) with carbonaceous matter, **B.** Ripple laminated sandstone with clay clasts.

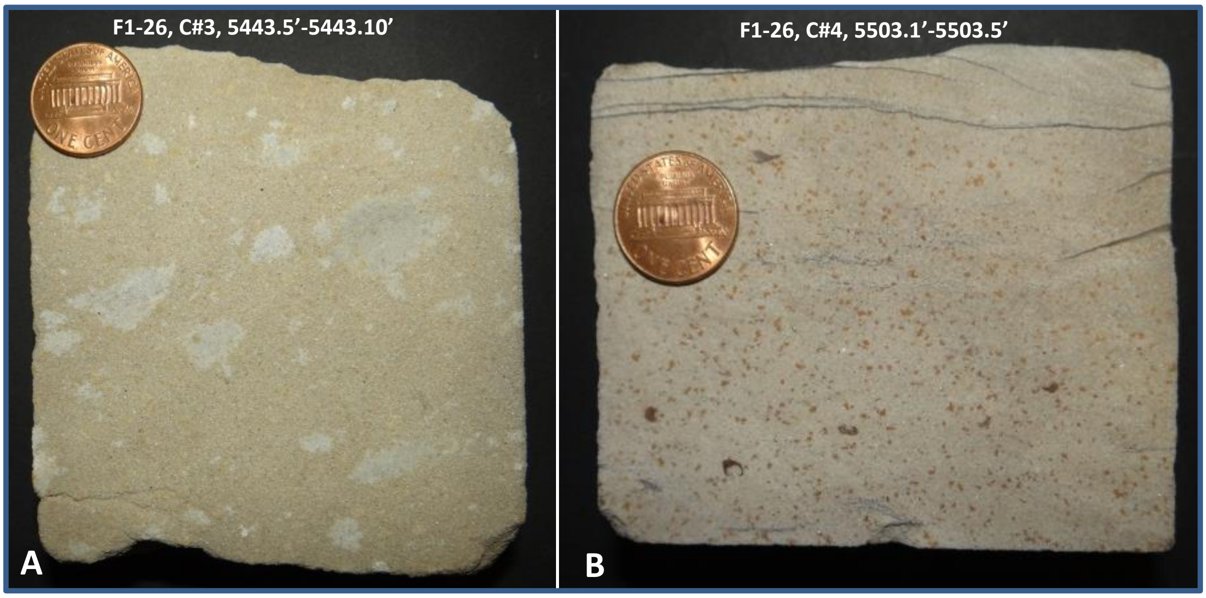


Figure 24. Slabbed core sample of lithofacies (6) in Tahara Formation, in well (F1-26), concession NC7A, Ghadames Basin showing, **A.** Massive sandstone with coarse materials (lag deposits), **B.** Massive sandstone with mud clasts.

4.7 Lithofacies (7) Rippled and fossilliferous sandstone

This lithofacies, represented by the cored interval 5700' to 5748.6' in the type well A8-NC7A (App.I.1). It consists of massive to rippled laminated sandstone. The sandstone is yellowish gray, very fine-fine grained, well sorted, subangular-subrounded, micaceous, occasionally rippled bedding, with clay clasts, flaser bedding also observed (App.I.2). The upper part represented in the interval from 5700'-5712.9', with streak of black shale about 0.2 inch, fossilliferous (brachiopods and pelecypods) at places (Figs. 25A-B).

Similar lithofacies was recognized in the area of A12-NC7A to the northeast (App.I.7), consisting of gray- light gray, very fine to fine grained, well sorted, subangular-subrounded sandstone, massive and occasionally wavy and rippled laminated with clay clasts, low oil stained (App.I.8), some streaks of slightly bioturbated shale and silty shale were observed, also fossil remains has been observed (Figs. 25C-D).

In the area of A13-NC7A north of the Gullebi Field, similar lithofacies has been observed (App.I.10), and it consists of light-dark gray, fine grained, micaceous, planar cross bedded sandstone (Fig. 26), occasionally massive, with clay clasts and some laminae of carbonaceous materials (App.I.11). The rippled laminations to planar laminations regime with the presence of rip up clasts and fossils fragments may indicate wave-action, high energy condition of probably beach zone.

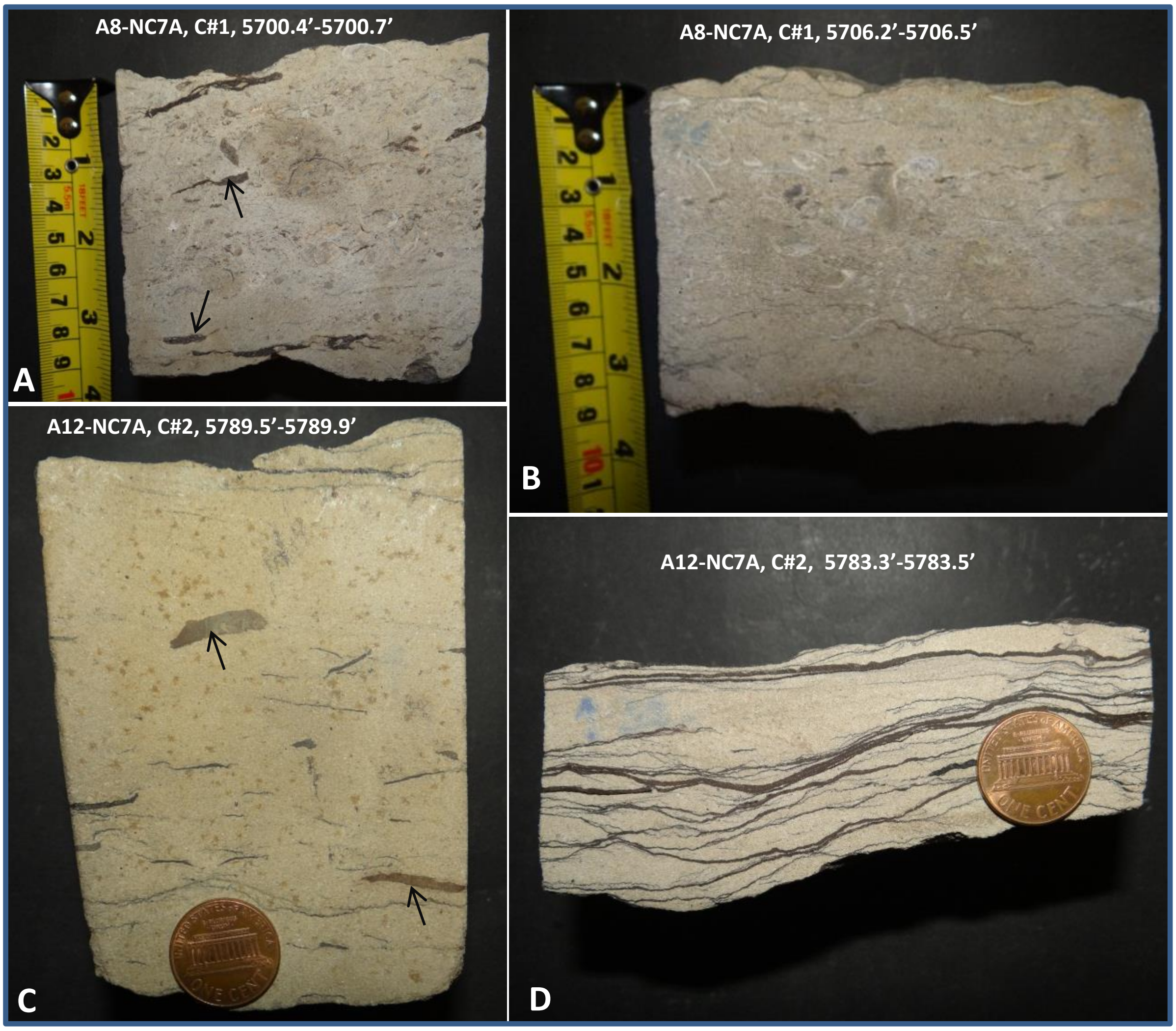


Figure 25. Slabbed core sample of lithofacies (7) in Tahara Formation, in wells (A8-NC7A&A12-NC7A), concession NC7A, Ghadames Basin showing, **A.** Fossiliferous sandstone with rip up clasts (arrows), **B.** Fossilileferous sandstone with Pelecypods fragments, **C.** Laminated sandstone with rip up clasts (arrows)**,** **D.** Wavy and rippled laminated sandstone.

Figure 26. Slabbed core sample of lithofacies (7) in Tahara Formation, in well (A13-NC7), concession NC7A, Ghadames Basin showing, planar laminated sandstone with angular basal contact and current direction from right to left.

Chapter (5)

Petrography of Tahara Formation

5.1 Modal analysis

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 (in Zuffa, 1985) and the description scheme of Harwood (1988). Modal analysis for the examined thin sections of Tahara Formation was conducted as shown in Tables (2, 3, 4 and 5), and location of examined thin sections is shown on (App.I.2-App.I.3, App.I.5-App.I.6, App.I.8-App.I.9, App.I.14-App.I.15, App.I.17 and App.I.19), where the result of this modal analysis was plotted on Ternary diagram (Fig. 27).

Table. (2) Modal composition of thin section samples from Tahara Formation

Framework grains, cement and matrix	Slide No								
	1	2	3	4	5	6	7	8	9
Quartz	240	275	266	134	192	239	235	263	240
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
Chamosite (iron-rich sh. pellets)	0	0	0	0	0	0	0	0	0
Clay matrix	0	0	0	65	0	0	0	0	0
Clay cement	0	0	0	39	7	4	0	10	6
Silica cement	10	9	20	2	18	16	21	19	17
Calcite cement	18	0	2	0	41	0	0	0	0
Total	300	300	300	300	300	300	300	300	300

Table. (3) Modal composition of thin section samples from Tahara Formation

Framework grains, cement and matrix	Slide No								
	10	11	12	13	14	15	16	17	18
Quartz	127	120	210	138	234	255	187	191	252
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
Chamosite (iron-rich sh. pellets)	0	0	0	75	0	0	0	0	0
Clay matrix	0	5	5	55	0	0	1	0	0
Clay cement	2	20	30	25	14	0	0	3	0
Silica cement	7	9	13	0	20	7	9	8	13
Calcite cement	0	0	34	0	0	0	0	71	0
Total	300	300	300	300	300	300	300	300	300

Table. (4) Modal composition of thin section samples from Tahara Formation

Framework grains, cement and matrix	Slide No								
	19	20	21	22	23	24	25	26	-
Quartz	181	228	232	250	239	216	248	217	-
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	-
Chamosite (iron-rich sh. pellets)	0	0	0	0	0	0	0	0	-
Clay matrix	0	3	5	0	0	15	0	0	-
Clay cement	2	45	9	0	16	22	0	0	-
Silica cement	11	10	20	9	11	14	20	14	-
Calcite cement	84	0	2	15	0	0	0	62	-
Total	300	300	300	300	300	300	300	300	-

Table. (5) Porosity types and percentages (%) for some selected samples in the sandstones of Tahara Formation.

Sample No.	Primary %		Secondary %			Total %
	Intergranular	Intercrystaline	Moldic	Solution	Fracture	
1	1	1	1	9	0	12
2	3	1	0	16	0	20
3	3	1	1	15	0	20
4	0	0	4	1	0	5
6	1	1	2	11	0	15
8	1	0	0	8	0	9
9	1	1	0	10	0	12
15	2	1	1	14	0	18
16	1	0	0	4	0	5
17	0	0	0	2	0	2
18	2	1	1	13	0	17
19	0	0	0	2	0	2
21	2	1	0	9	0	12
22	0	0	0	4	0	14
23	0	0	0	1	0	1
24	0	0	0	0	0	0
-	2%	1%	2%	8%	0%	-
Total Average 11%						

5.2 Detrital composition

The Tahara sands have a high microfracture quartz content, which constitute most of the Tahara sands for an average of about (86%) of the total sand grains, and an average of 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), and after plotting of all studied thin sections (Fig. 27) 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.

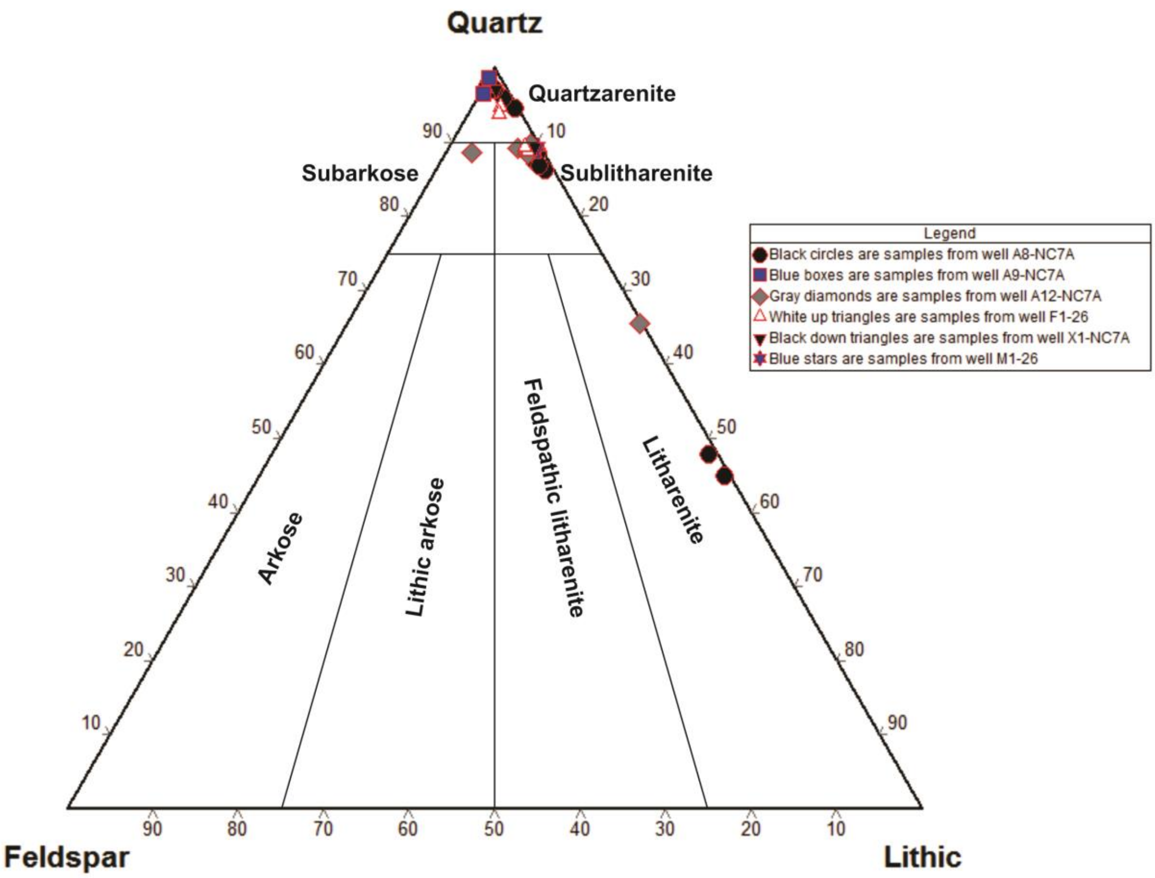


Figure 27. Detrital composition of sandstone thin sections of the Tahara Formation plotted in Ternary QFL diagram, (QFL classification of sandstones after Folk, 1980).

5.2.1 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. 28). Most of the quartz grains are characterized by straight contact (grain supported). Quartz grains are intensively fractured, may be of tectonic origin.

5.2.2 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 subangular detrital grains (Fig. 28), and it is commonly dissolved and replaced by kaolinite.

5.2.3 Rock fragments

Rock fragments represents 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 (Figs. 29 and 30).

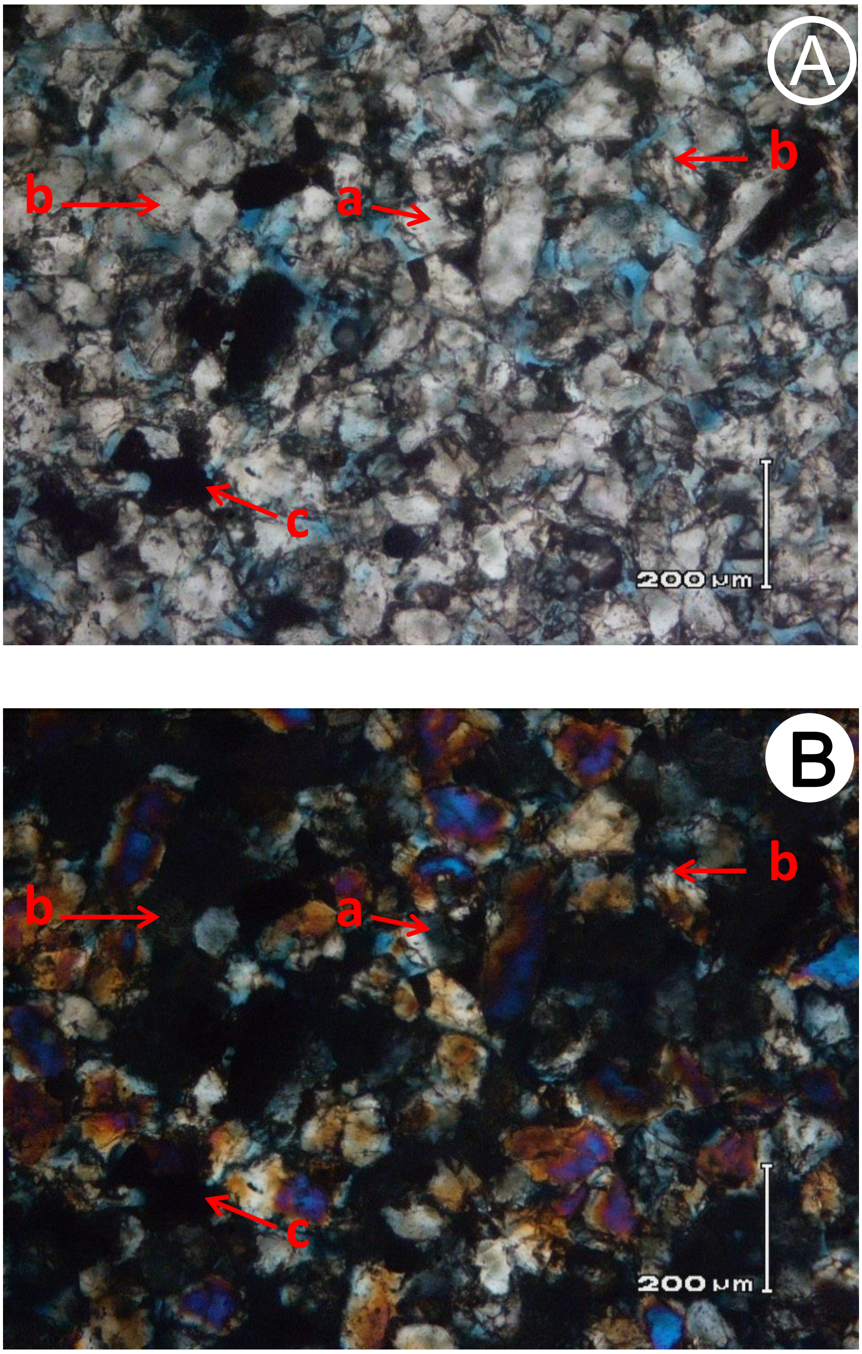


Figure 28. A. Thin section photomicrograph (18) of rippled and fossilliferous sandstone lithofacies, sublitharenite, in Tahara Formation, showing (a) Quartz, (b) Feldspar and (c) Clay clasts, core # 2 at 5782.2ft., well A12-NC7A (PPL). **B.** Same thin section but in (XPL).

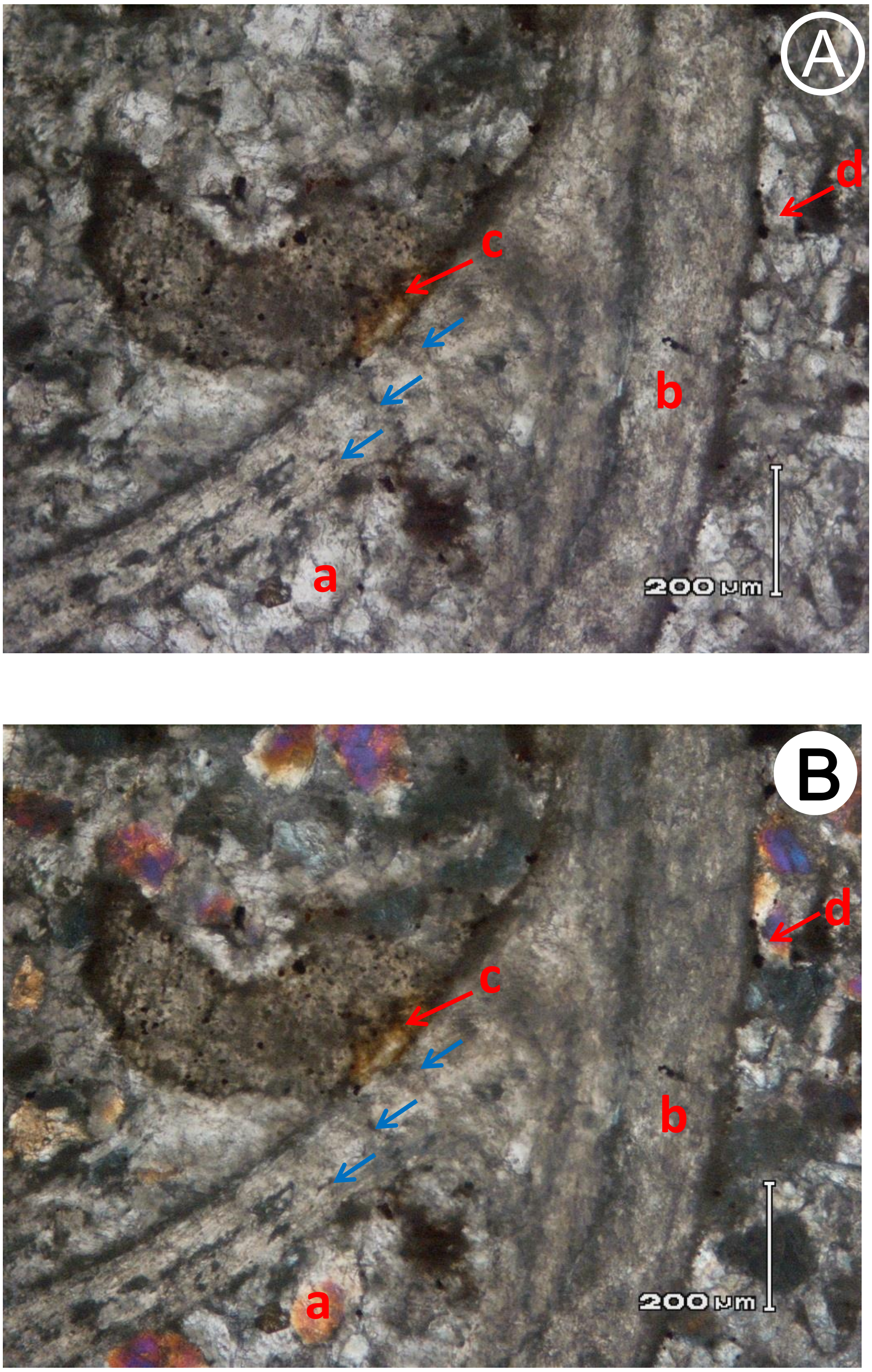


Figure 29. A. Thin section photomicrograph (10) of rippled and fossilliferous sandstone lithofacies, litharenite, in Tahara Formation, showing (a) Quartz, (b) Pelecypod fragment occasionally with cross-lameller texture (blue arrows) at places, (c) Clay matrix, and (d) Feldspar, core # 1 at 5706.2ft., well A8-NC7A (PPL). **B.** Same thin section but in (XPL).

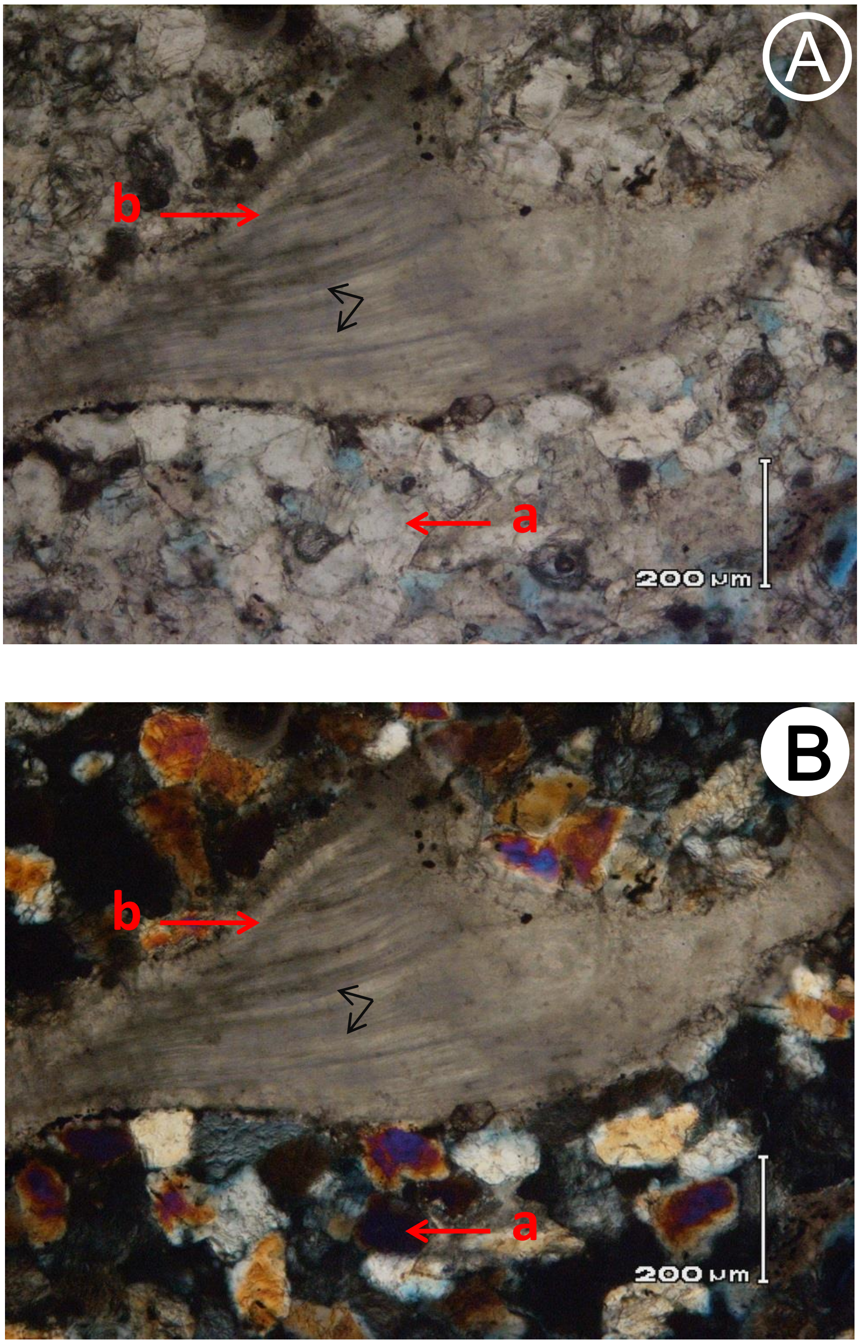
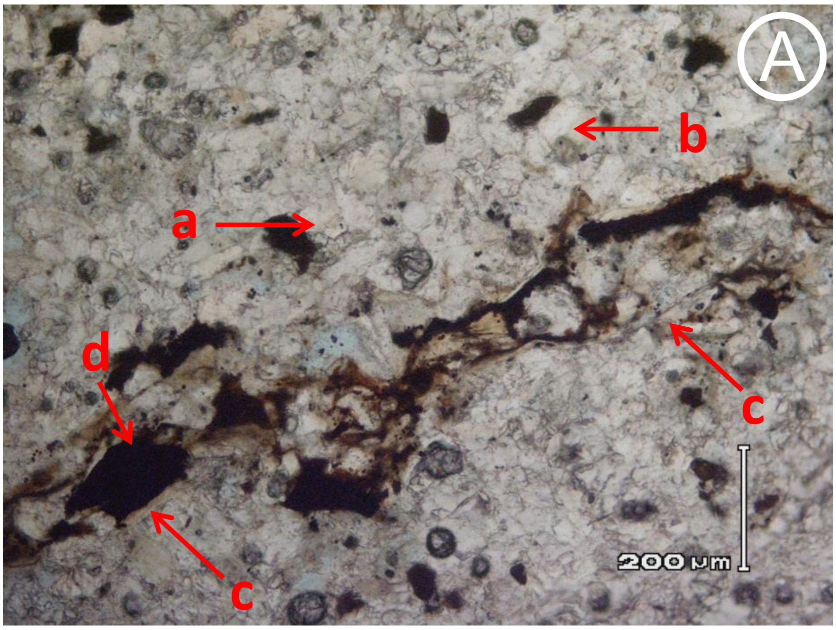


Figure 30. A. Thin section photomicrograph (16) of rippled and fossilliferous sandstone lithofacies, litharenite, in Tahara Formation, showing (a) Quartz, (b) Brachipod shell fragment with low-angle fibrous wall structure (arrows), core # 3 at 5796ft., well A12-NC7A (PPL). **B.** Same thin section but in (XPL).

5.2.4 Accessory minerals

The most common accessory minerals associated with the Tahara sands are the opaque minerals (organic materials), 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. 31).

Detrital glauconite exist locally up to 18%, and recognized by its green color under both (PPL and XPL) (Fig. 32). 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 pelletal to oolitic texture between quartz grains in thin section of well A9-NC7A. These iron-rich structures have occurred under weakly oxidizing to mildly reducing conditions and the changes of grains may have been promoted by certain bacterial action (Greensmith, 1988), (Figs. 33 and 34).



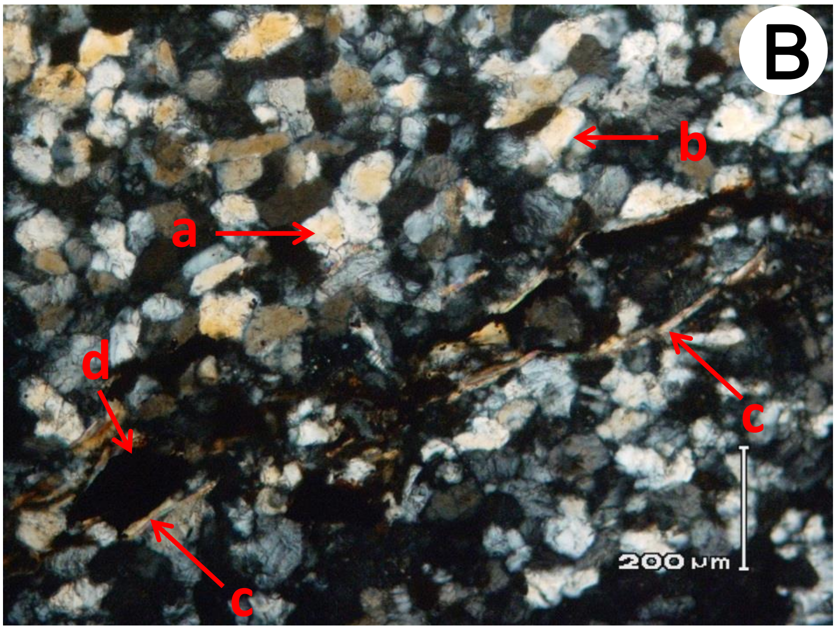


Figure 31. A. Thin section photomicrograph (23) of interlaminated shale and silty sandstone lithofacies, sublitharenite, in Tahara Formation, showing (a) Quartz, (b) Feldspar, (c) Mica muscovite and (d) Clay clasts, core # 2 at 5435ft., well F1-26 (PPL). **B.** Same thin section but in (XPL).

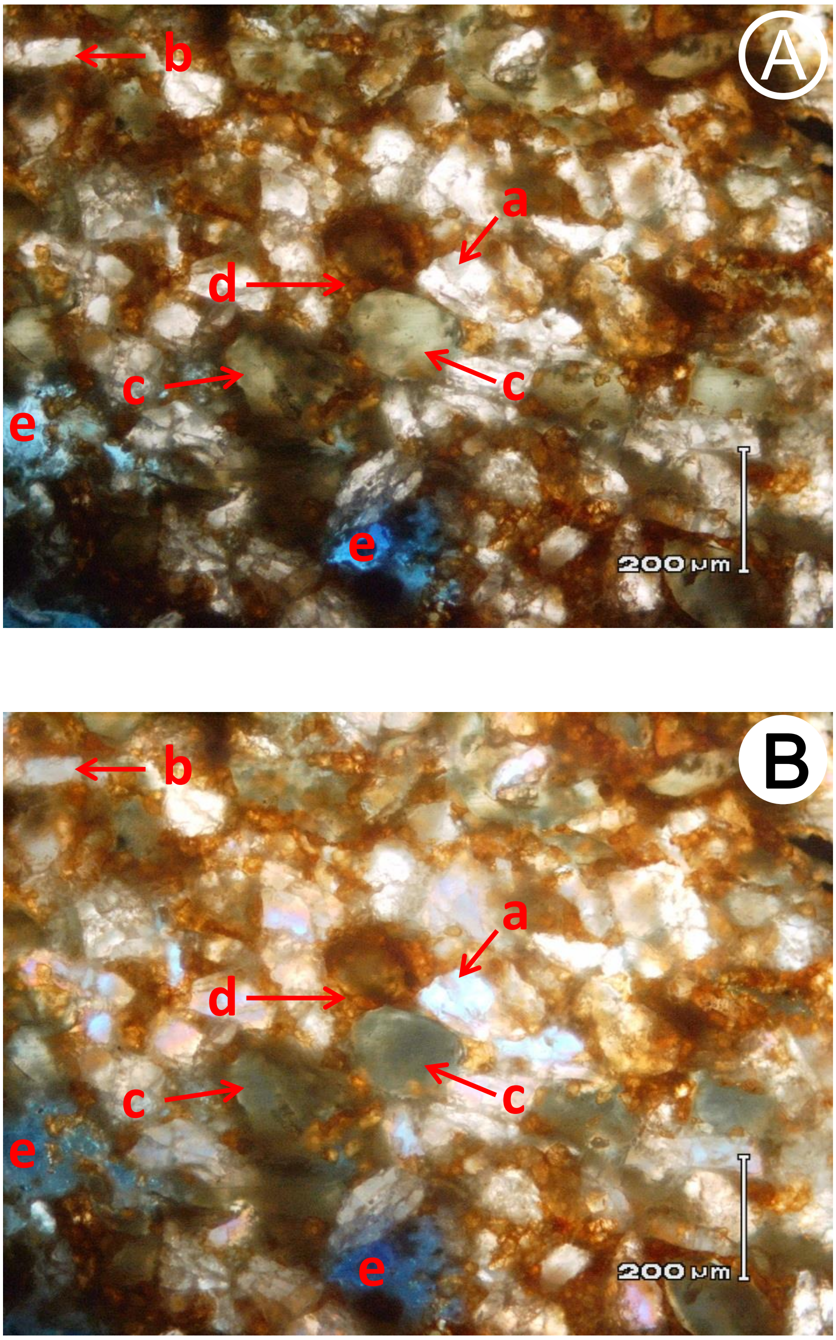


Figure 32. A. Thin section photomicrograph (4) of interlaminated shale and silty sandstone lithofacies, quartzarenite, in Tahara Formation, showing (a) Quartz, (b) Feldspar, (c) Glauconite, (d) Clay matrix and (e) Pore spaces, core # 2 at 5754.7ft., well A8-NC7A (PPL). **B.** Same thin section but in (XPL).

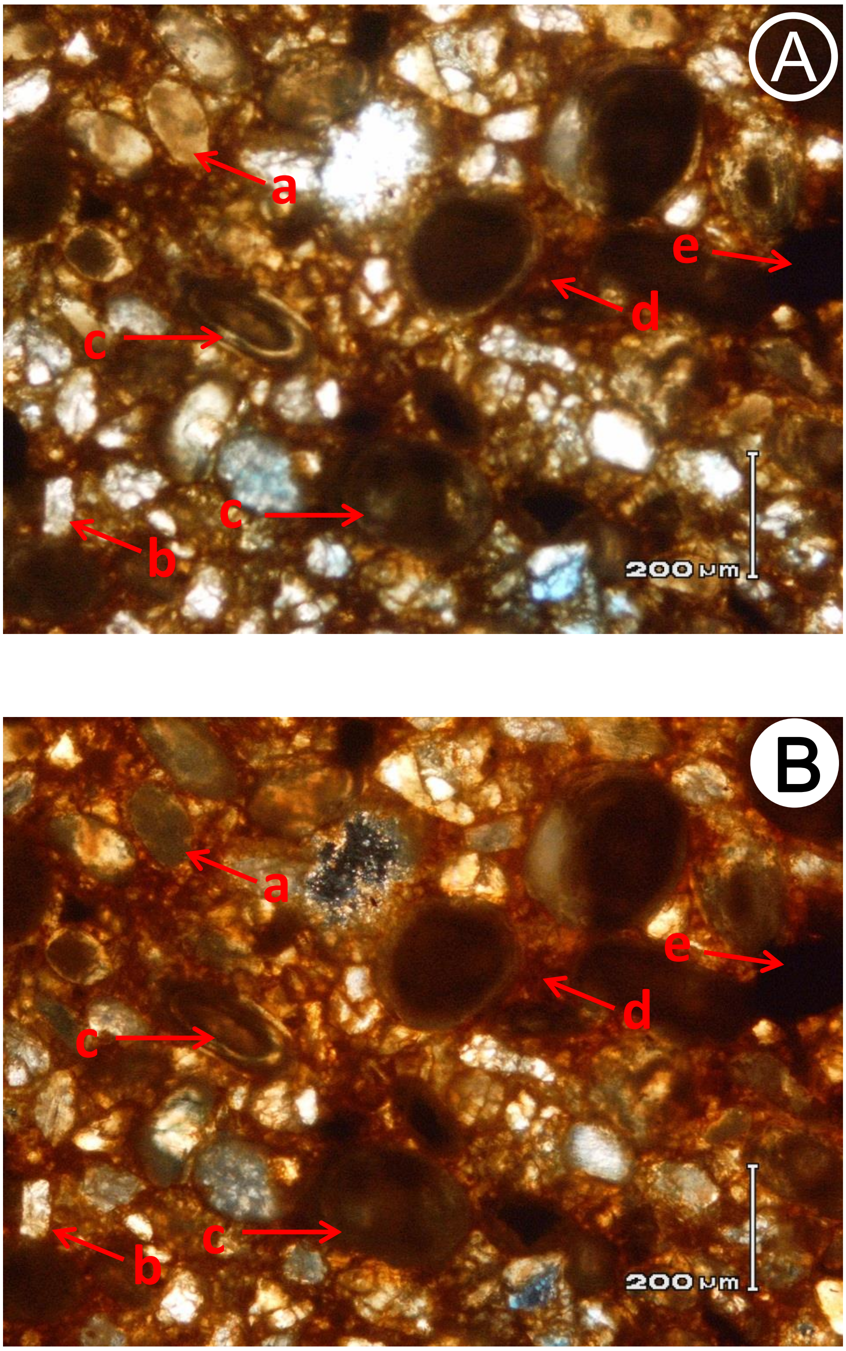


Figure 33. A. Thin section photomicrograph (13) of varicoloured silty shale and bioturbated iron-rich shale lithofacies, quartzarenite, in Tahara Formation, showing (a) Equant quartz grain, (b) Feldspar, (c) Chamosite grain (iron rich pellets), (d) Clay matrix and (e) Organic material, core # 3 at 5754ft., well A9-NC7A (PPL). **B.** Same thin section but in (XPL).

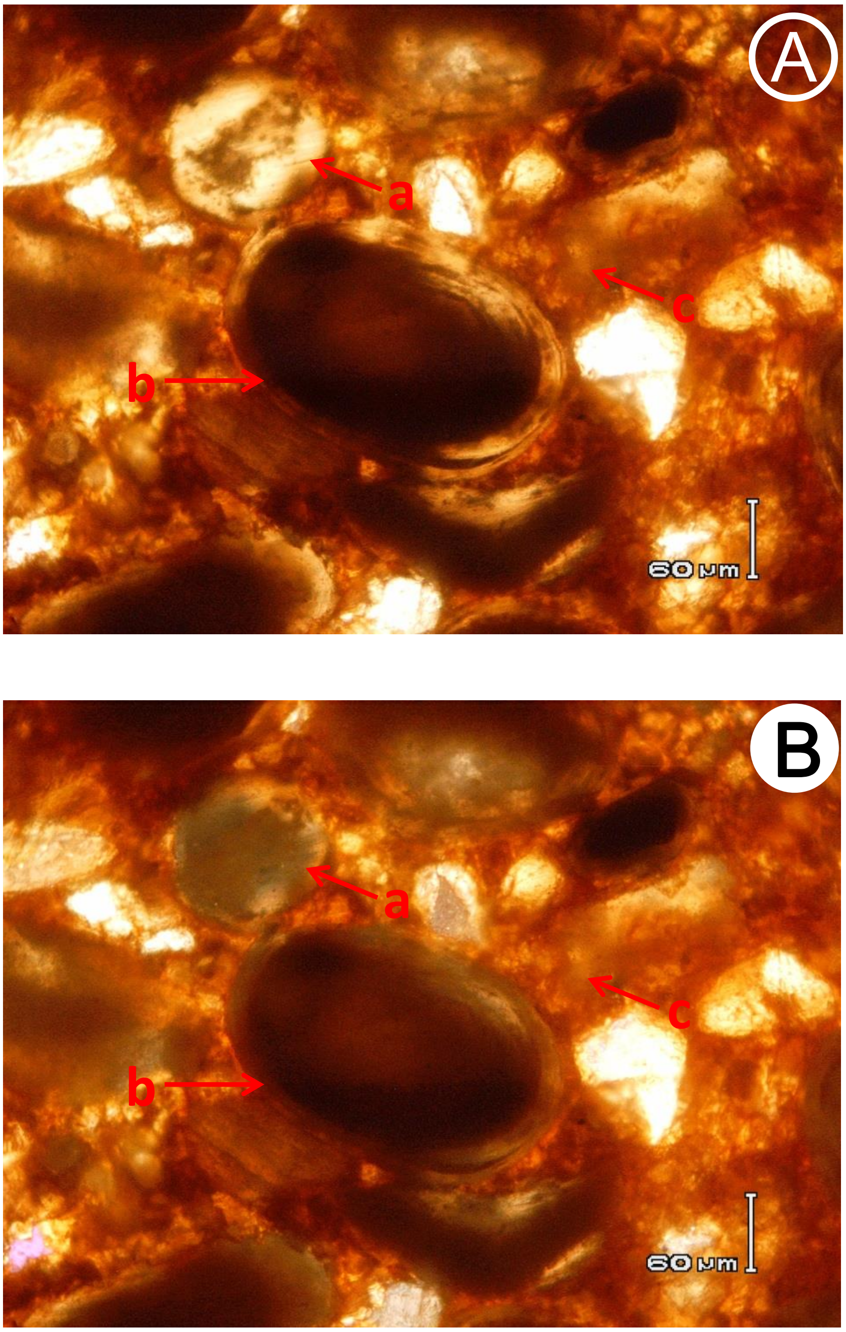


Figure 34. A. Detailed thin section photomicrograph (13) of varicoloured silty shale and bioturbated iron-rich shale lithofacies, quartzarenite, in Tahara Formation, showing (a) Equant quartz grain, (b) Chamosite grain (iron rich pellets) and (c) Clay matrix, core # 3 at 5754ft., well A9-NC7A (PPL). **B.** Same thin section but in (XPL).

5.3 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. 35), other quartz grains may show overgrowth between adjacent grains (Fig. 36). Silica cement is the most common type of cements in the Tahara sandstone and it ranging from 0% to 7% (Tables 2-4). 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 0% to 28% in quartz grain supported samples as calcite cement may be inferred to post-dated quartz overgrowths (Tables 2-4) (Fig. 37).

Kaolinite cement ranging from 0 to 15% is present in the interlaminated shale and silty sandstone lithofacies, as pore-filling replacive to feldspar reduces porosity and characterized by stippled texture (Fig. 38).

5.4 Clay matrix

Clay matrix comprises a low percentages of about 0 % in most of the studied thin sections, while it is dominantly filling pore spaces with high percentages of about 22% in the varicoloured silty shale and bioturbated iron-rich shale lithofacies (Tables 2-4). Clay matrix may be generated by mechanical compaction of quartz, feldspar grains and lithic fragments or as a result of bioturbation at some places (Figs. 32-34). Illite was encountered as pore filling and occasionally replaces kaolinite in sandstone (Fig. 36).

5.5 Porosity

The recorded intregranular/intercrystalline primary porosity is ranging from 1 to 2% in the studied thin sections and mainly reduced by early quartz overgrowth (Figs. 35, 36 and 39), where intergranular porosity is more common in bioturbated sand and shale lithofacies (Fig. 42) (see Table. 5). However, secondary porosity by dissolution is more dominating the studied thin sections and reached up to 8%, as a result of partial or total dissolution of rock fragments and feldspar grains (Figs. 40 and 41).

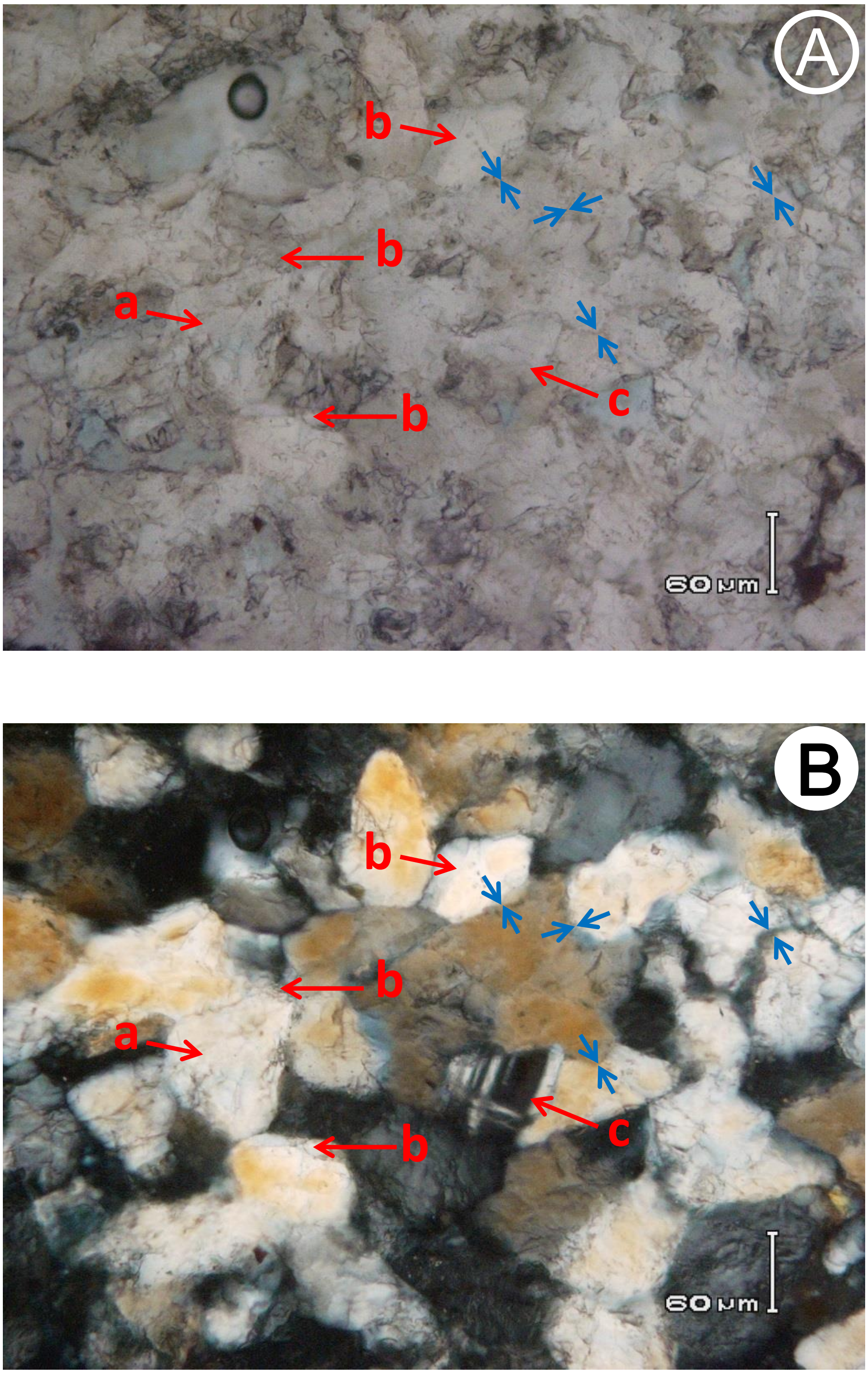


Figure 35. A. Detailed thin section photomicrograph (22) of massive sandstone and gravel lithofacies, quartzarenite, in Tahara Formation, showing (a) Quartz, (b) Quartz overgrowth and (c) Feldspar plagioclase. Blue arrows refer to pressure solution area, core # 3 at 5448.7ft., well F1-26 (PPL). **B.** Same thin section but in (XPL).

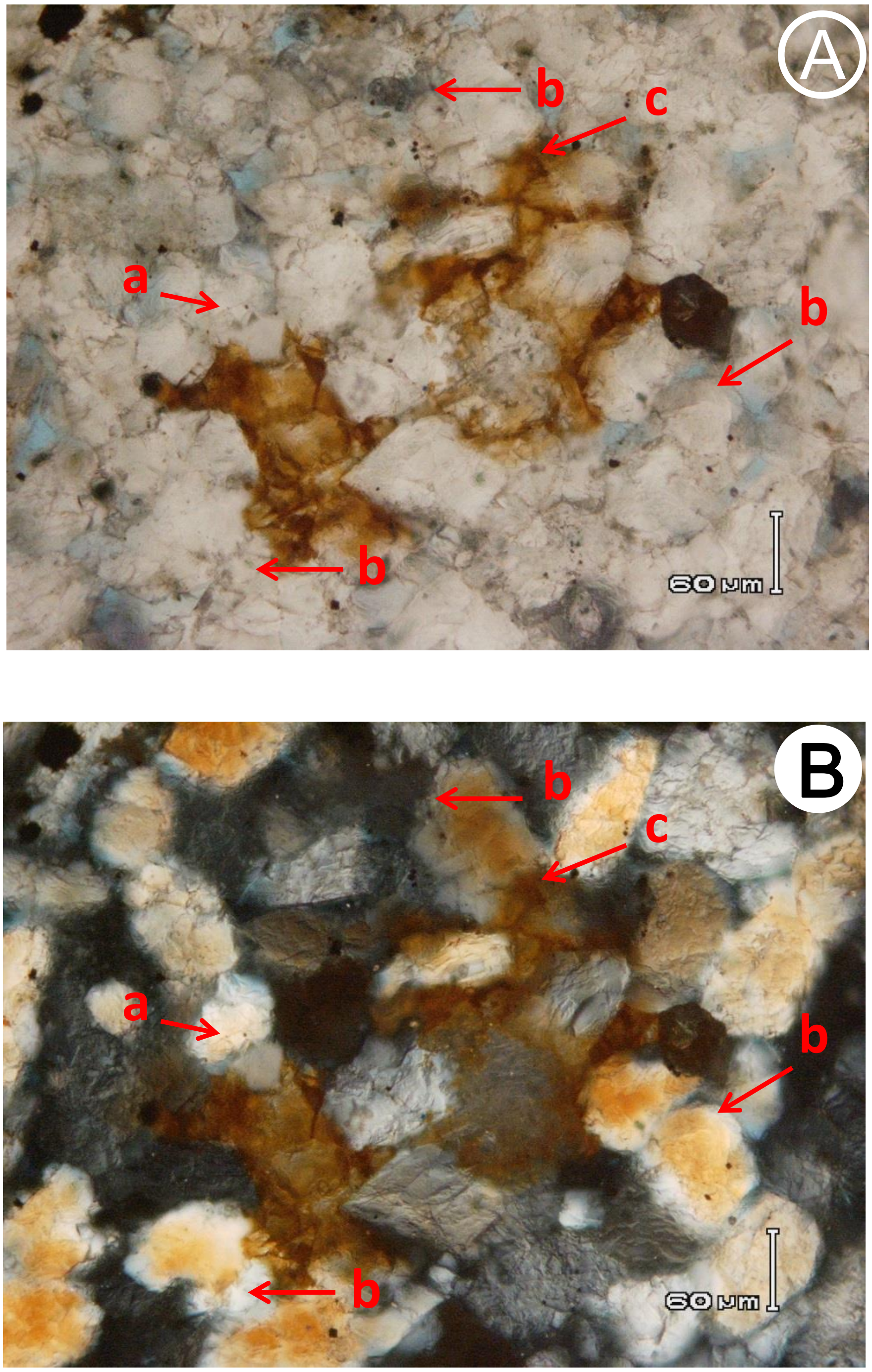


Figure 36. **A.** Detailed thin section photomicrograph (8) of massive sand and gravel lithofacies, quartzarenite, in Tahara Formation, showing (a) Quartz, (b) Quartz overgrowth and (c) Clay cement (illite), core # 1 at 5719ft., well A8-NC7A (PPL). **B.** Same thin section but in (XPL).

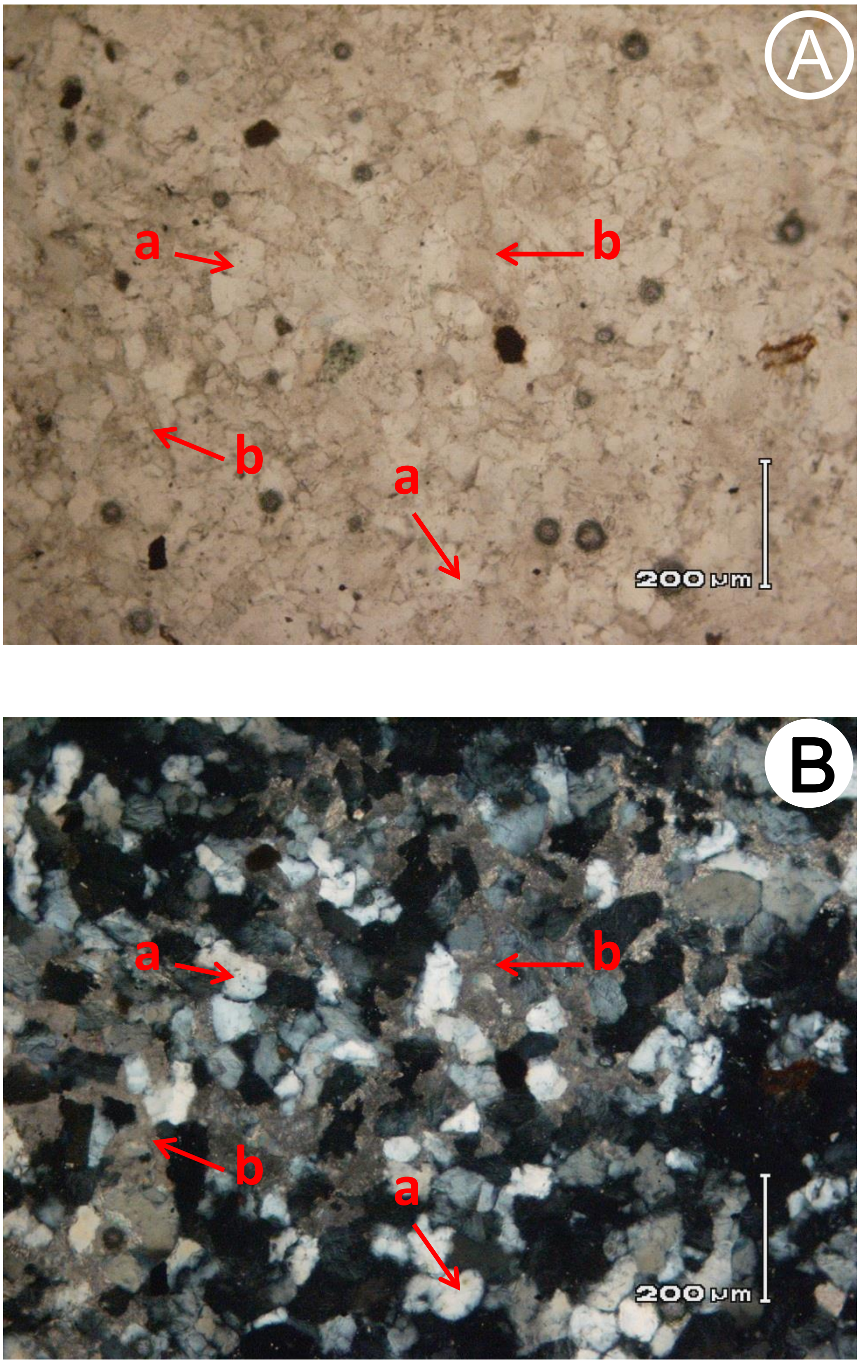


Figure 37. A. Thin section photomicrograph (26) of parallel laminated silty sandstone and silty shale lithofacies, quartzarenite, in Tahara Formation, showing (a) Quartz, and (b) Calcite cement, core # 1 at 6199ft., well X1-NC7A (PPL). **B.** Same thin section but in (XPL).

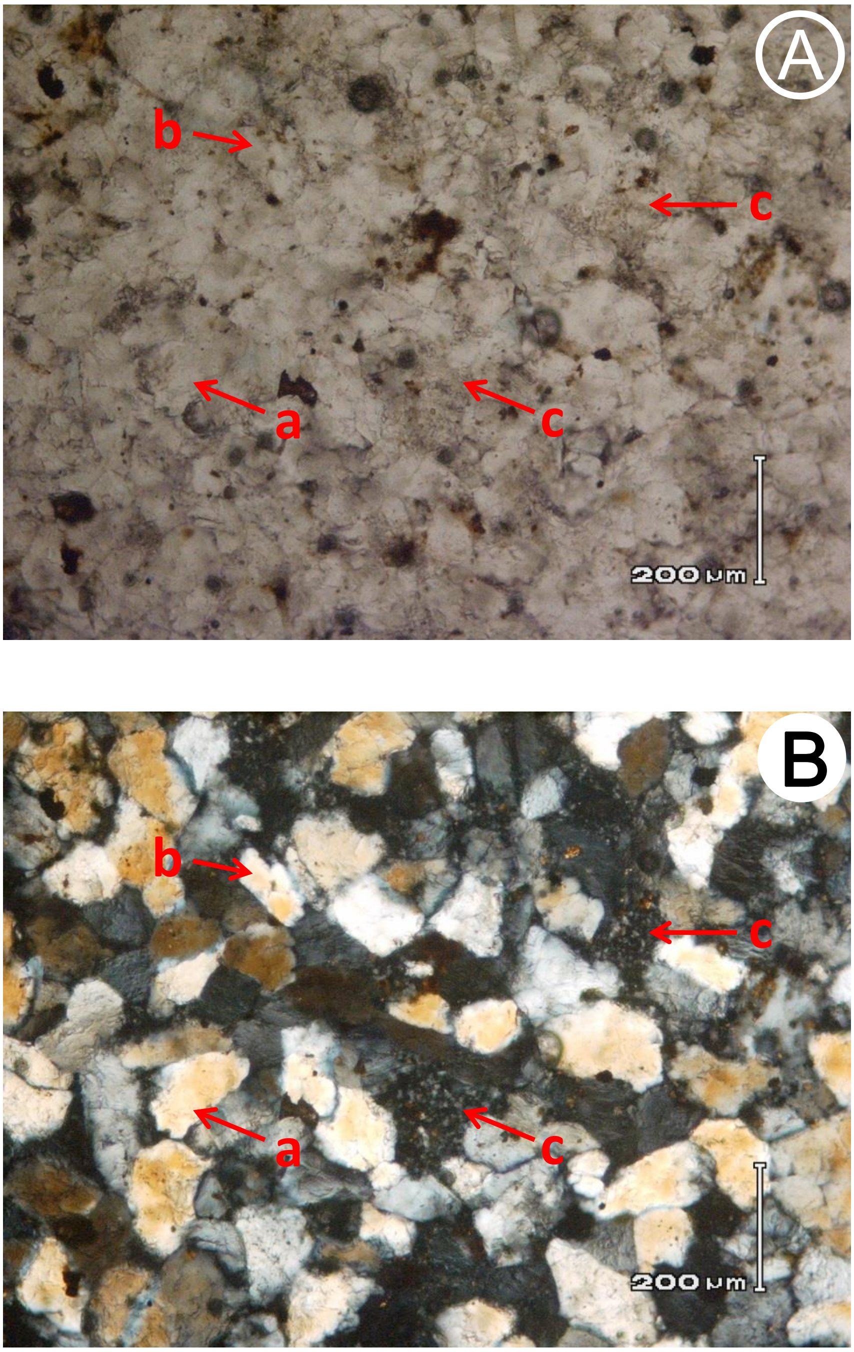
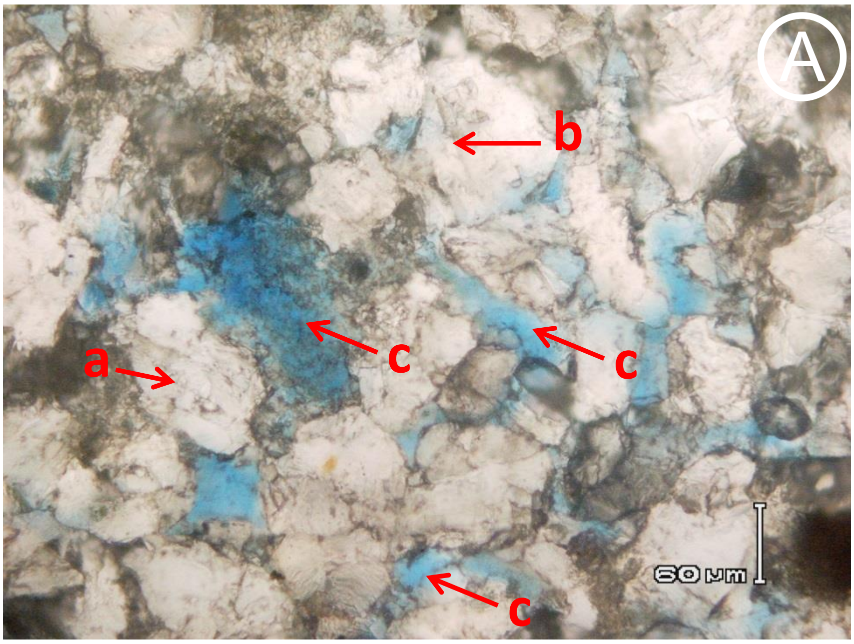


Figure 38. A. Thin section photomicrograph (14) of interlaminated shale and silty sandstone lithofacies, sublitharenite, in Tahara Formation, showing (a) Quartz, (b) Feldspar and (c) Clay cement (kaolinite) filling pore spaces, core # 1 at 5703ft., well A9-NC7A (PPL). **B.** Same thin section but in (XPL).



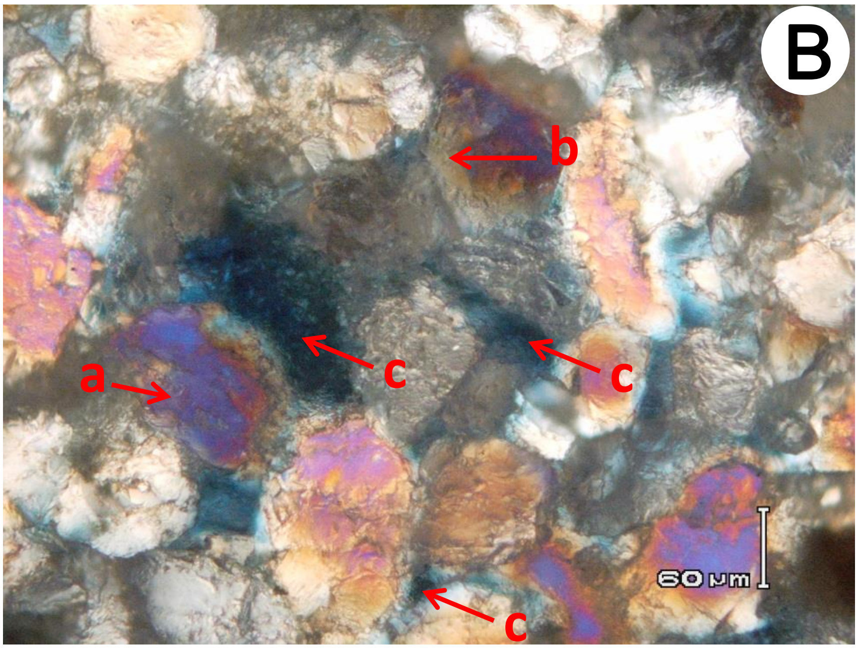


Figure 39. A. Detailed thin section photomicrograph (3) of bioturbated sand and shale lithofacies, quartzarenite, in Tahara Formation, showing (a) Quartz, (b) Quartz overgrowth and (c) Pore spaces, core # 4 at 5790.11ft., well A8-NC7A (PPL). **B.** Same thin section but in (XPL). Quartz and feldspar grains (crystals) in this thin section are varying in colors (from blue or violet to brown or yellowish brown) show anomalous birefringence due to thicker thin section (> 30 µm).

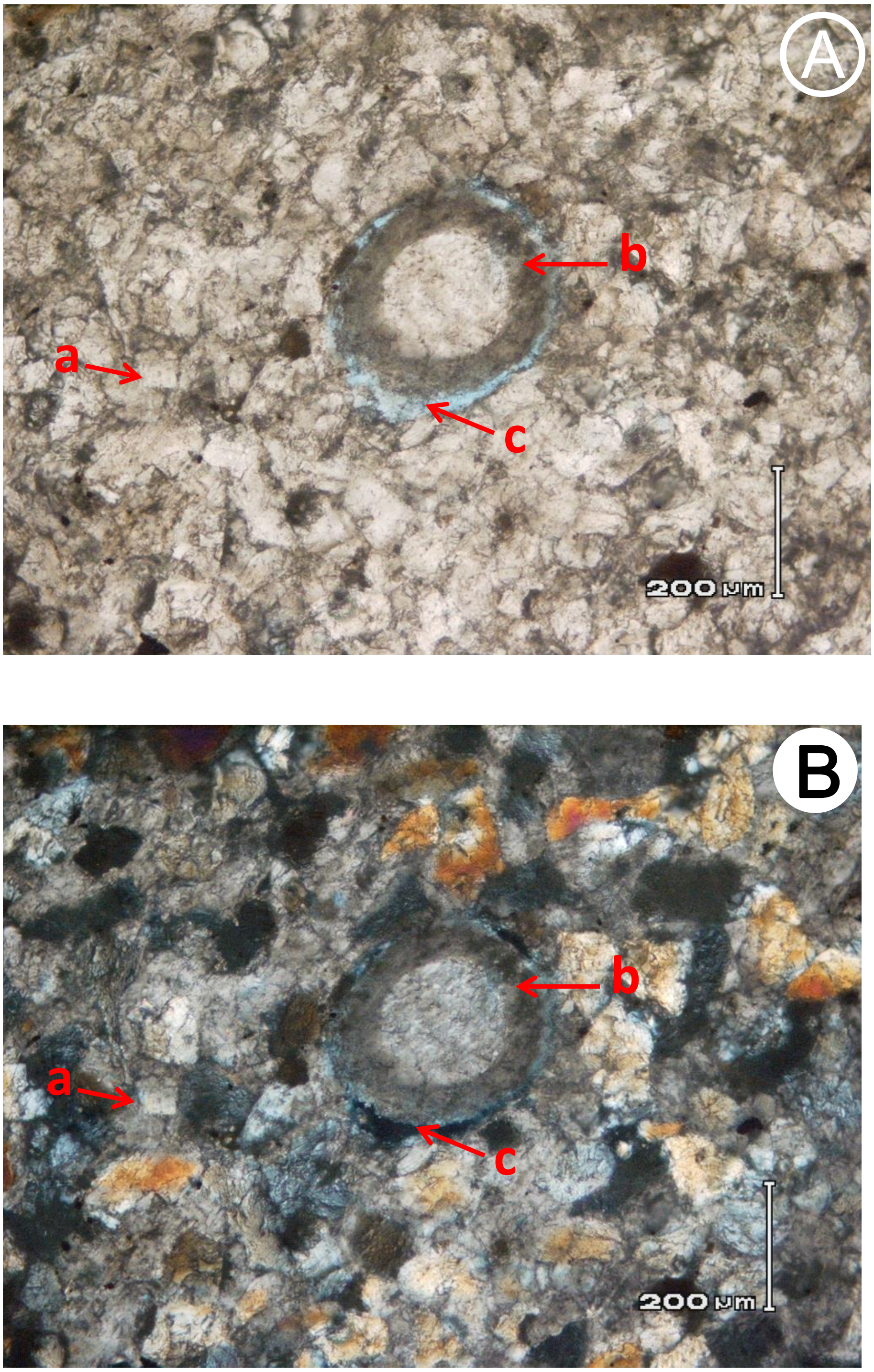
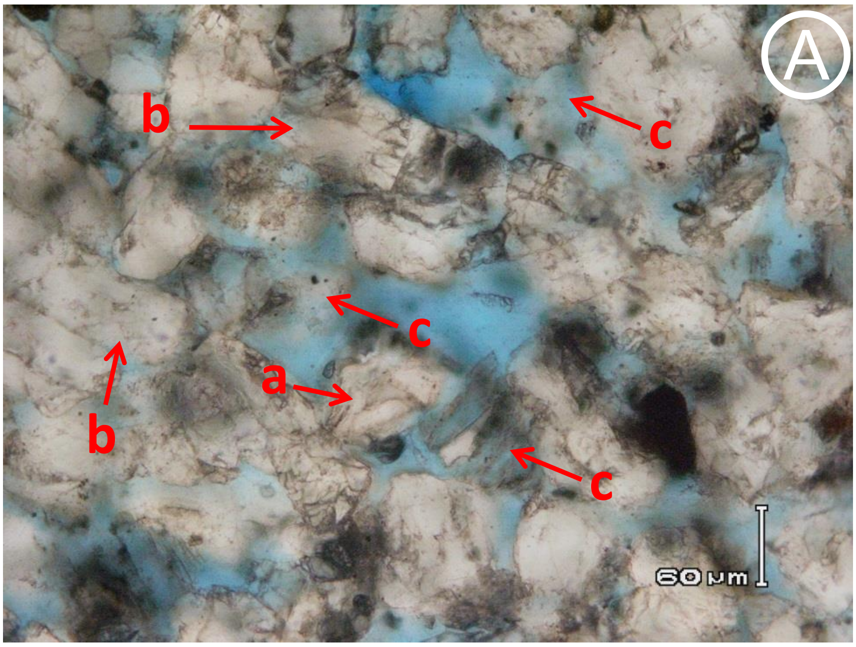


Figure 40. A. Thin section photomicrograph (10) of rippled and fossilliferous sandstone lithofacies, litharenite, in Tahara Formation, showing (a) Quartz, (b) Ring structure of brachipod spine filled with quartz grains, (c) Shrinkage dissolution porosity, core # 1 at 5706.2ft., well A8-NC7A (PPL). **B.** Same thin section but in (XPL).



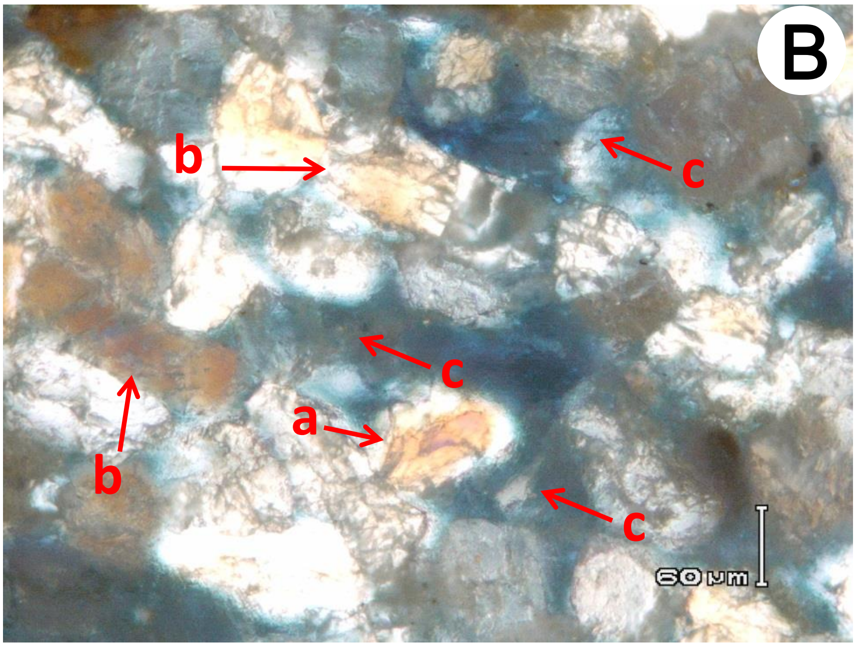
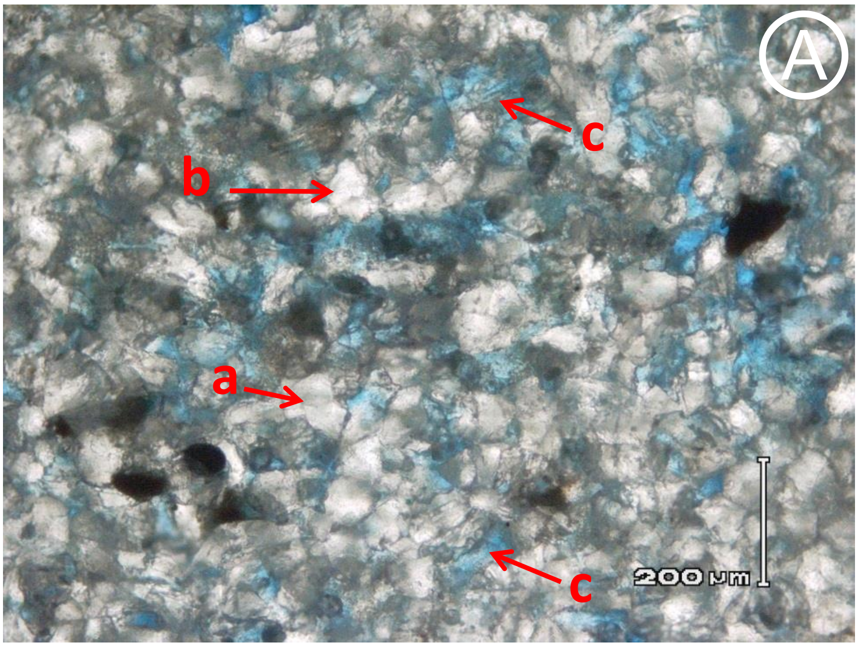


Figure 41. A. Detailed thin section photomicrograph (15) of interlaminated shale and silty sandstone lithofacies, subarkose, in Tahara Formation, showing (a) Quartz, (b) Feldspar of lath like shape and (c) Feldspar dissolution, core # 4 at 5828.10ft., well A12-NC7A (PPL). **B.** Same thin section but in (XPL).



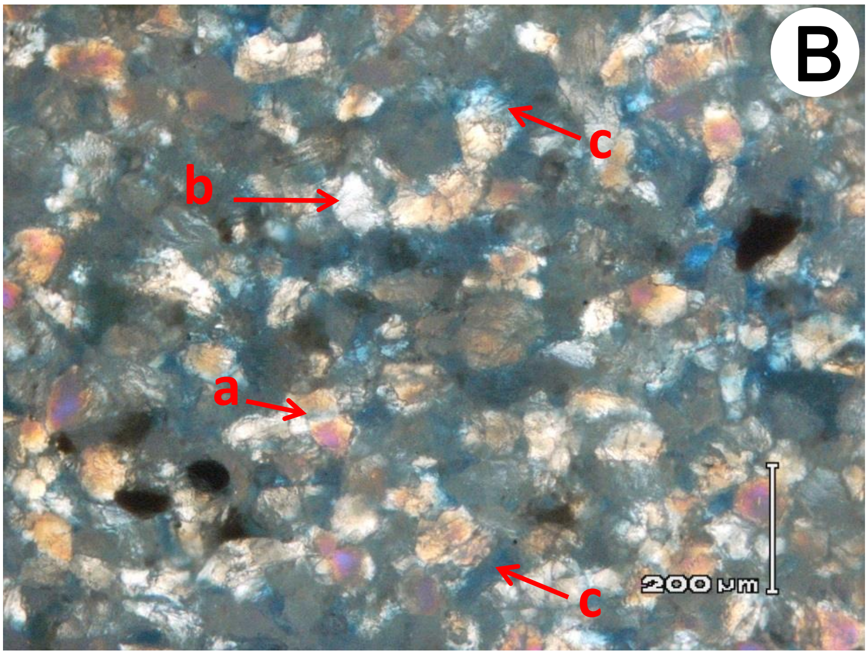


Figure 42. A. Thin section photomicrograph (2) of bioturbated sand and shale lithofacies, quartzarenite, in Tahara Formation, showing (a) Quartz, (b) Feldspar and (c) Feldspar grains leaching porosity due to partial of dissolution, core # 5 at 5820.7ft., well A8-NC7A (PPL). **B.** Same thin section but in (XPL).

Chapter (6)

Diagenetic Constituents

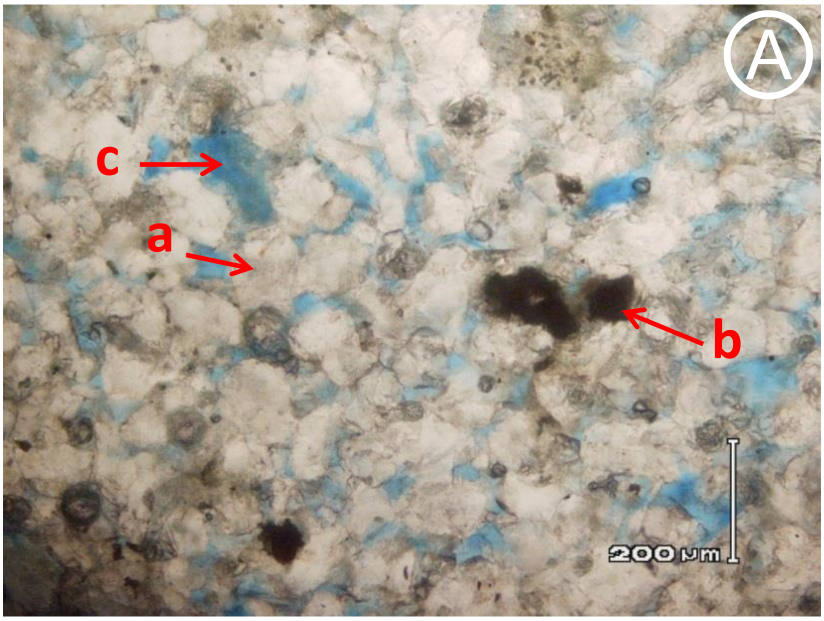
The diagenetic processes and their products may be identified as such: The fabric of studied sandstones exhibit mechanical compaction at early stage of their deposition (Figs. 35A&B). The percentage of primary porosity loss due to compaction and early quartz overgrowth cementation and partially due to later calcite cementation. Secondary enhancement due to mainly labile grain dissolution and fracturing. Secondary porosity loss may be due to mainly pore filling clay matrix.

6.1 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. 43) consists of very fine-fine occasionally medium grained sandstone, well sorted, quartzarenite (Sample No. 3, Table 2) and of rare mud clasts (3%) and no clay matrix (0%) associated with beach-proximal deltaic sandstone. The total cementation in this lithofacies is up to (8%) composed mainly of quartz overgrowth (7%), with no clay filling pores (0%) with patches of calcite cement (1%). The primary porosity is partially preserved and the secondary porosity was generated by grain dissolution with total porosity (20%) (Table 5).
2. Medium quality lithofacies association (Fig. 44) comprises fine-medium grained sandstone, well-poorly sorted, with feldspar to lithic primary composition (sublitharenite) (Sample No. 21, Table 4) and of some mud clasts (9%) and matrix (2%) associated with fluvial channel sandstone. The total cementation in this lithofacies is up to (11%) composed mainly of quartz overgrowth (7%), clay filling pores (3%) with calcite cement (1%). The primary porosity is partially preserved and the secondary porosity was generated by grain dissolution with total porosity (12%) (Table 5).
3. Low quality lithofacies association (Fig. 45) consists of silty-very fine grained sandstone, poorly sorted, with lithic primary composition of sublitharenite texture (Sample No. 24, Tables 4 and 5) with abundant mud clasts (9%) and matrix (5%)

associated with marginal deltaic sandstone. The total cementation in this lithofacies is up to (12%) composed mainly of quartz overgrowth (5%), clay filling totally pore spaces (7%) and no calcite cement (0%). The primary and secondary porosity are totally blocked (0%) (Table 5).



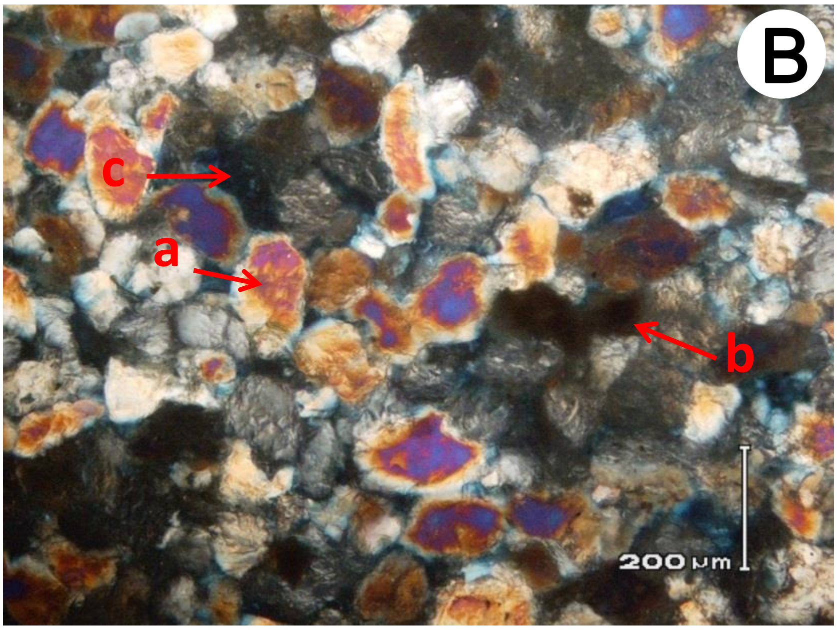
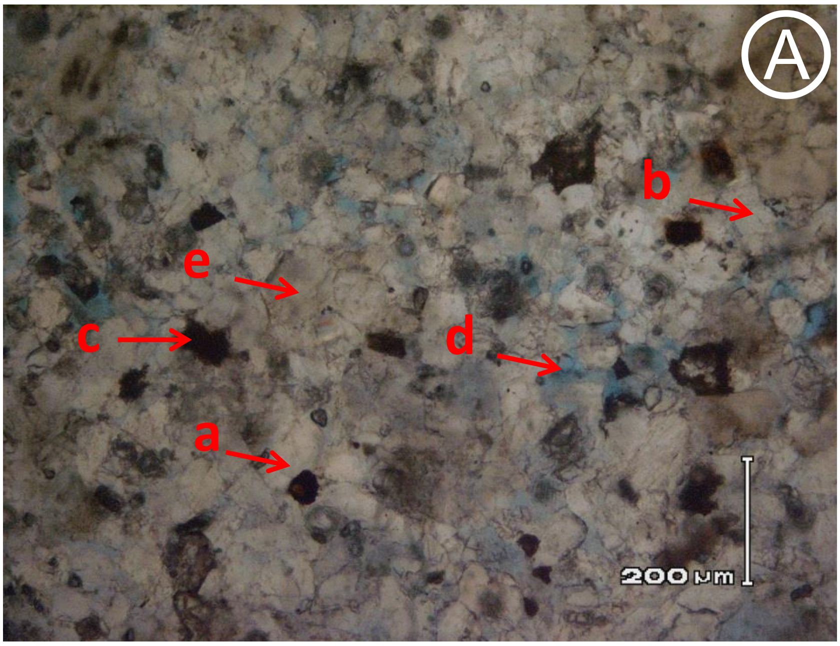


Figure 43. A. Thin section photomicrograph (3) of good quality lithofacies association in bioturbated sand and shale lithofacies (beach-proximal deltaic sandstone), quartzarenite, in Tahara Formation, showing (a) Quartz, (b) Clay clasts and (c) Pore space (partial primary and secondary porosity), core # 4 at 5790.11ft., well A8-NC7A (PPL). **B.** Same thin section but in (XPL).



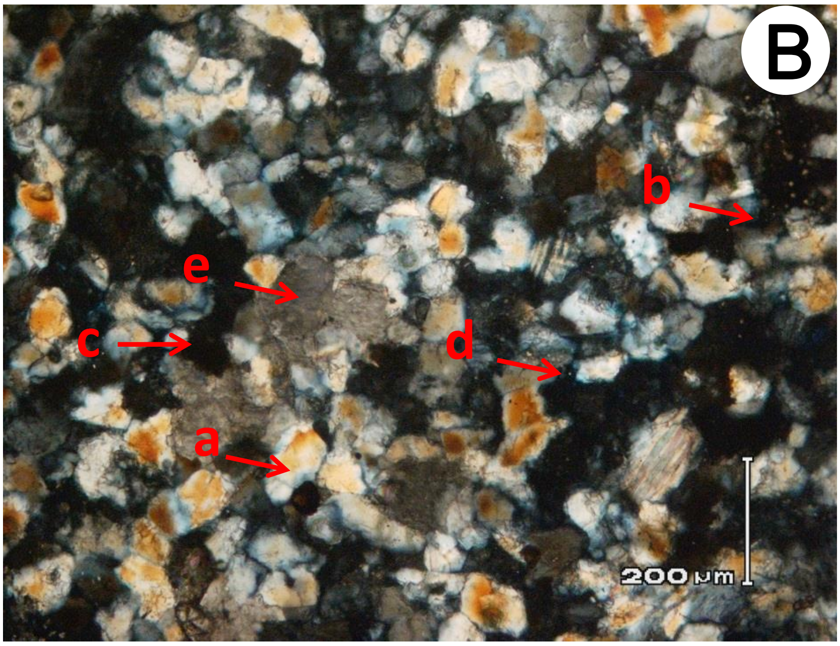
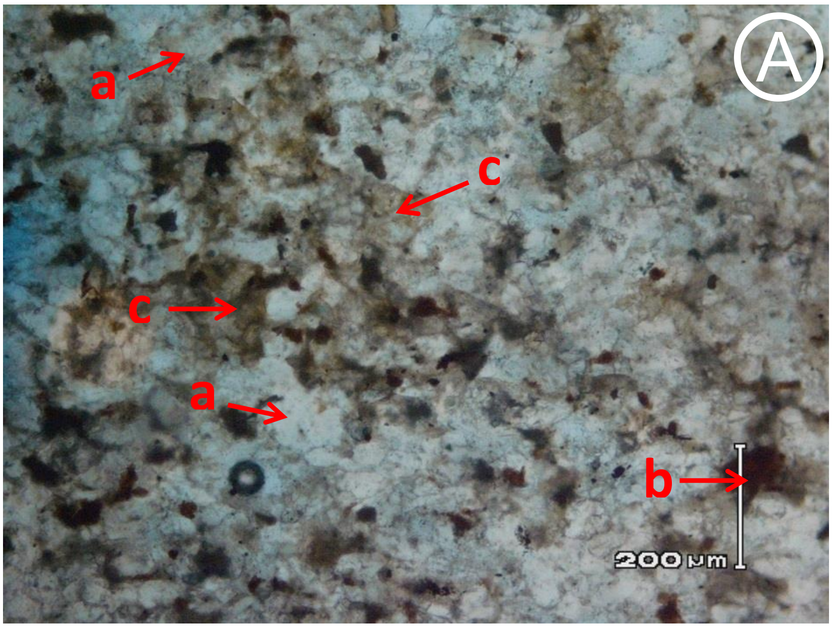


Figure 44. A. Thin section photomicrograph (21) of medium quality lithofacies association in massive sandstone and gravel lithofacies (fluvial channel sandstone), sublitharenite, in Tahara Formation, showing (a) Quartz, (b) Feldspar, (c) Clay clasts, (d) Pore space (primary porosity is rarely preserved with some secondary porosity) and (e) Clay matrix filling partially pores, core # 4 at 5502.11ft., well F1-26 (PPL). **B.** Same thin section but in (XPL).



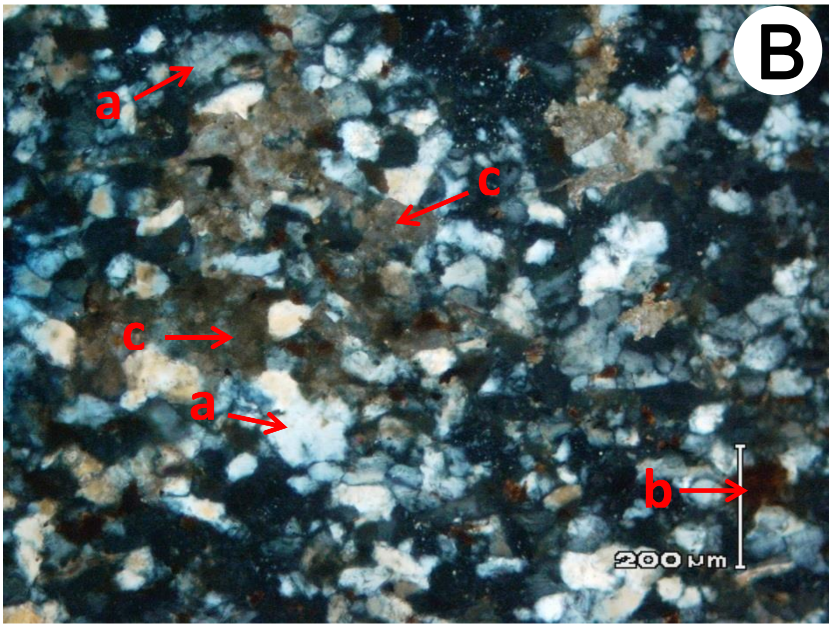


Figure 45. A. Thin section photomicrograph (24) of low quality lithofacies association in interlaminated shale and silty sandstone lithofacies (marginal deltaic), sublitharenite, in Tahara Formation, showing (a) Quartz with quartz overgrowth, (b) Clay clasts (filling partially pore spaces) and (c) Clay matrix (filling totally pore spaces), core # 7 at 6205ft., well M1-26 (PPL). **B.** Same thin section but in (XPL).

6.2 Impact of diagenetic constituents in reservoir quality 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 (Morton-Thompson and Woods, 1993).

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), 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.

Chemical compaction occurs by dissolution and precipitation of solids and are controlled by thermodynamics and kinetics (Fig. 46). 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 siliceous sediments becomes “overconsolidated” preventing further mechanical compaction. Compaction at greater depth must therefore be modelled as a function of temperature integrated over time (BjΦrlykke et al., 2009). Petrographically, according to the studied thin sections of the Tahara sandstone, we believe that the chemical compaction represented by pressure solution and 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 cement in the remaining open pore spaces.

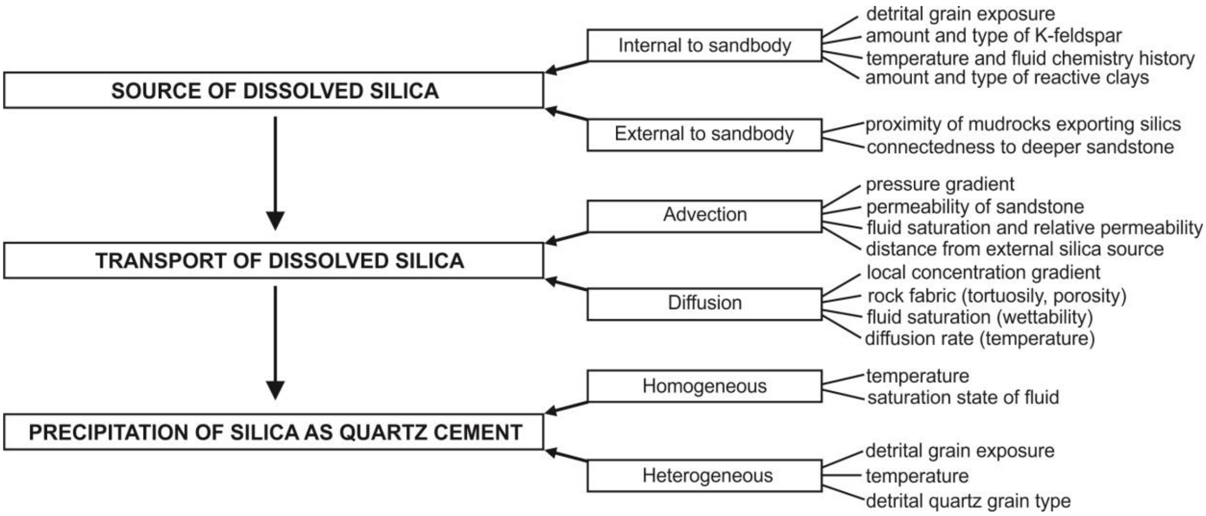


Figure 46. Schematic diagram for the geochemical controls on quartz cementation. The three fundamental controls are the rates of supply, transport and precipitation from aqueous solution. These have been subdivided into the key secondary controls and the main influences on the rate of these key secondary controls are listed on the right of the diagram (after Worden and Morad, 2000).

The presence of clay cement (kaolinite cement) had a major influence on reservoir quality of Tahara sandstone, where considerable amount of clay cement (in the form of clay clasts and kaolinite) and matrix (illite) 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 (Schmidt and McDonald, 1980). 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 in (Fig. 47).

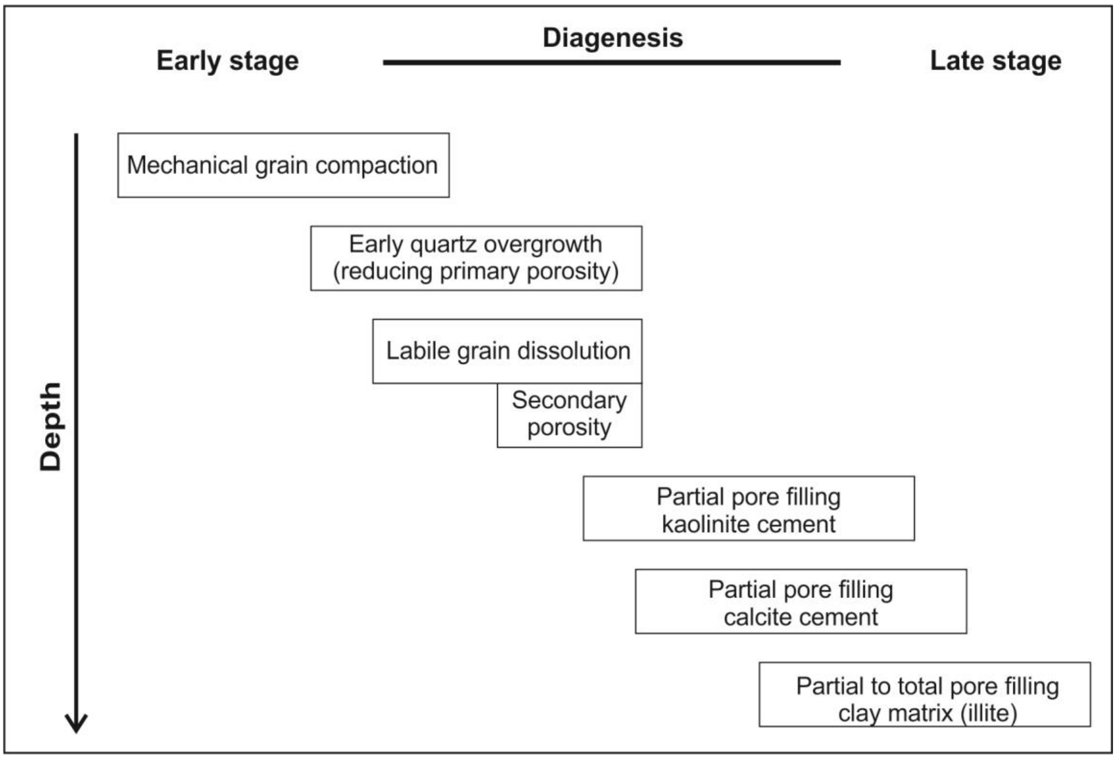


Figure 47. Paragenetic sequence for the Tahara sandstone in Gullebi Field.

Chapter (7)

Wireline-logs Characteristics, Paleogeography and Depositional Environment Model for Tahara Formation

7.1 Wireline-log characteristics

Wireline-logs are important tools for investigating facies sequences and usually supported by cores. As a result, where some core control is not available it should be possible to extrapolate environmental lithofacies into non cored wells on the basis of GR-log characteristics alone.

Wireline logs which are run routinely on most wells were examined as sedimentological tool for identifying different lithofacies types of Tahara Formation within studied wells. The SP-log characteristics also were investigated and compared with GR-curve for some wells. The most useful wireline log curve in the Tahara succession, is the Gamma ray (GR) log, where it is a common wireline log in the studied wells and the best log for lithological purposes because it is mostly influenced by rock properties and least influenced by fluid properties. So that, Gamma ray log shapes may be used to determine: (1) sediments grain-size; (2) minerology in sediments and (3) depositional facies and environments, (Selley 1976; Galloway and Hobday, 1983; Cant 1984; Rider 1990 in Burki, 1998). Moreover, Gamma ray shapes may represent clean and interbedded sandstone and shale sequences. and define abrupt and gradational contacts characterizing sequences. By using GR-log signature of Tahara Formation (Fig. 48) and for the sake of simplifying the complex inter relationship of different observed facies of Tahara Formation, it was necessary to subdivide Tahara Formation into lower sand sequence and upper sand sequence separated by an intermediate shale and silt interval (Fig. 48). Each of the lower sand sequence and upper sand sequence consists of some sand units as regarded by lower sand unit of lower sequence, upper sand unit of lower sequence. Likewise lower sand unit of upper sequence and upper sand unit of upper sequence (Fig. 48). Four well logs shape types were recognized in the studied wells (Fig, 48).

1. Funnel shape (coarsening upward sequence) which shows increasing energy of deposition (gradual increase in grain-size) and also decrease in clay contents, it is characterized by a gradational base and an abrupt sharp top. This found to correspond with beach, bars, coastal sands or deltaic deposits (progradationl system).

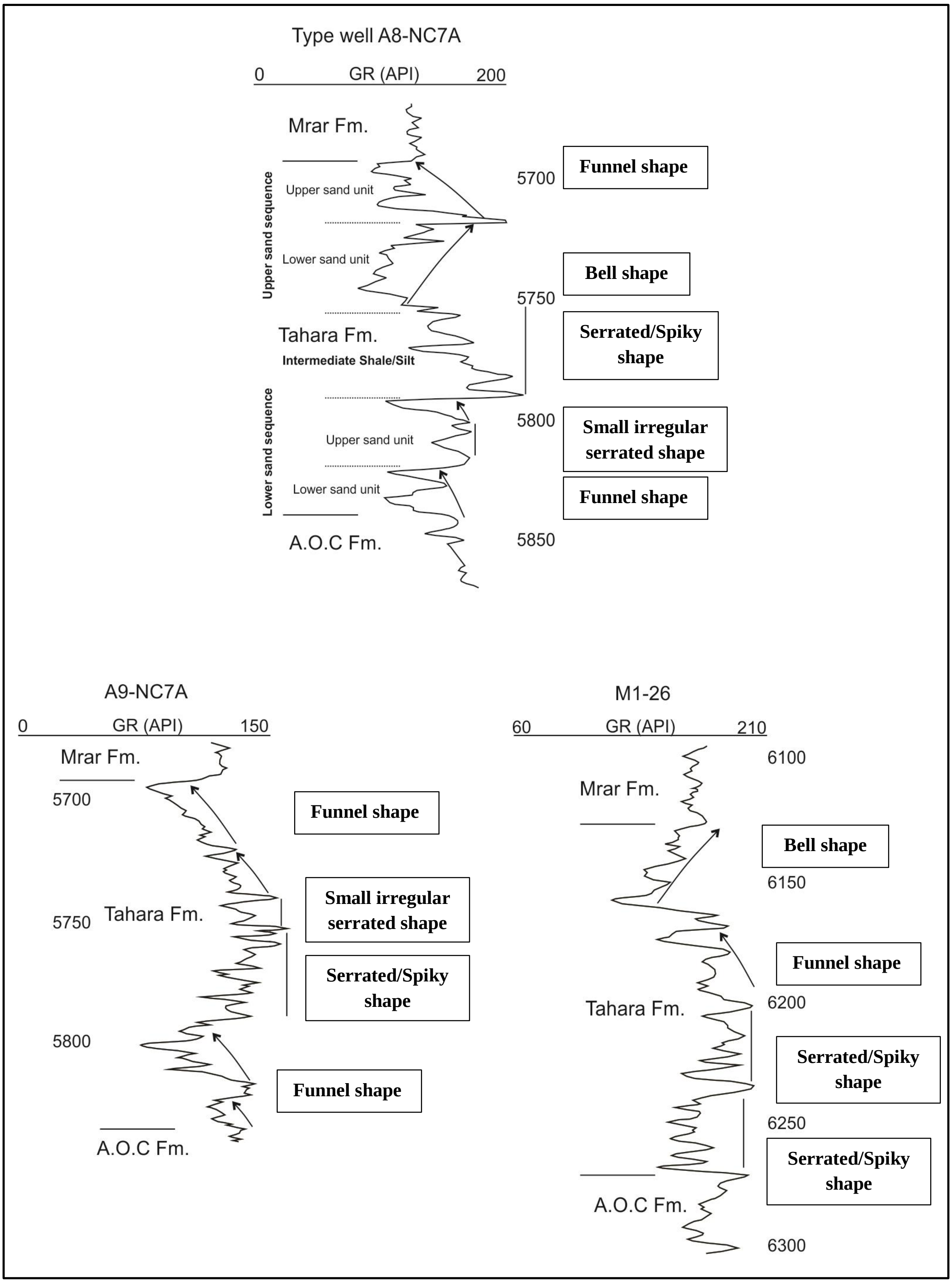


Figure 48. GR-log motifs for the sandstone units of Tahara Formation as represented by type well (A8-NC7A) and other studied wells A9-NC7A & M1-26, concession NC7A, Ghadames Basin, NW Libya.

2. Bell shape (finning upward sequence) characterized by a sharp basal contact, representing decreasing depositional energy (decrease in grain-size) and also increase in clay content towards the top. This tends to correspond with interpreted channel sand sequences
3. Serrated to spiky shape which shows occasionally small pulses of fining or coarsening log-signature. The serrated nature usually corresponds to the presence of shale/silts and sands interbeds. Generally this trend is indicating of transgressive and deep marine slope to basinal shale/silt sequences.
4. A few small scale irregular serrated sands and shale show a GR curve that has a sharp base and is inclined to the left (suggesting finning upward), core description indicate their iron-rich nature with some bioturbation associated with coastal plain deposits corresponds to lagoonal-mud flat lithofacies

7.2 Paleogeography

For paleogeographic regards, stratigraphic units undergo thickness and facies changes across a basin, reflecting contemporaneous paleogeography, subsidence patterns, and location of sediment sources. Most of these aspects of basin development are controlled by tectonics, the development of bounding faulted or folded uplifts, and subsidence caused by thermal contraction of continental margins, basement failure, or thrust-sheet loading. Eustatic sea-Ievel changes are also of profound paleogeographic importance. Such effects leave their imprint on sediments via their control on paleoslope by the structuring of land masses that guide oceanic currents, wave advance, or air flow and by the development of depocenters and their control on water depths or rates of internal scour (Miall, 2000).

7.2.1 Stratigraphic cross section (Time stratigraphic unit)

Stratigraphic cross sections show characteristics of correlatable stratigraphic units, such as reservoir sandstones or sealing shales. They may also be vital in understanding the timing of deformation by showing the drape of sediment over developing folds or the thickening of the section across growth faults. Stratigraphic sections should be oriented perpendicular to depositional strike (dip direction) to show facies changes toward or away from the basin margin. Strike sections parallel to the basin margin should be drawn to show lateral variations of particular beds or sequences. In the tectonic context of a basin, these axes are also structural axes (Morton-Thompson and Woods, 1993).

To insure accurate correlation and to illustrate certain structural, stratigraphic, and sedimentological relationships, two stratigraphic cross sections have been generated. The first is strike section constructed parallel to the strike direction (Fig. 49 and Encl. 1) and the second is dip section, constructed parallel to the depositional dip direction (Fig. 50 and Encl. 2). The base of the transgressive Lower Carboniferous Mrar Formation which directly overlying the Tahara sandstone was utilized as a stratigraphic datum for both cross sections, which is considered to represent flat time-line between correlated wells. Detailed study of the two cross sections was carried-out and could be summarized as following:

The strike cross section (Fig. 49 and Encl. 1) is trending NE-SW parallel or nearly parallel to the Gullebi Field and may be display the least amount of stratigraphic variation because all correlated wells located on this cross-section were at nearly the same water depth. However, this detecting some incised valleys or channel systems in the vicinity of well A4-26 in the NE and the vicinity of wells A1-26, A8-NC7A and A17-NC7A in the SW as they cut deep and between shoreline facies (Beach sandstone) where the interruption and discontinuity along shoreline facies variations and the action of channel erosion can be quite pronounced.

The dip cross section (Fig. 50 and Encl. 2) is trending NW-SE crossing the Gullebi Field and more or less parallel to the Tahara Formation depositional dip. This cross section passes from relatively landward at one end in SE direction where fluvial channels are dominating the area in vicinity of wells PP1-66 and F1-26 to relatively seaward end in NW direction, where these channels are prograded to transition zone of more coastal-deltaic to beach sediments domination especially in the vicinity of wells A7-NC7A, A10-NC7A, A12-NC7A, A9-NC7A and X1-NC7A. These sand types are eventually passes through shelf slope and basin area characterized by silt/shale interbeds and enclosed thin marine sand bars at the vicinity of well M1-26. Locally at the top of the Tahara Formation in well M1-26, a small scale finning upward GR signature which may be attributed to sub aquatic channel and infers deposition in deep basin.

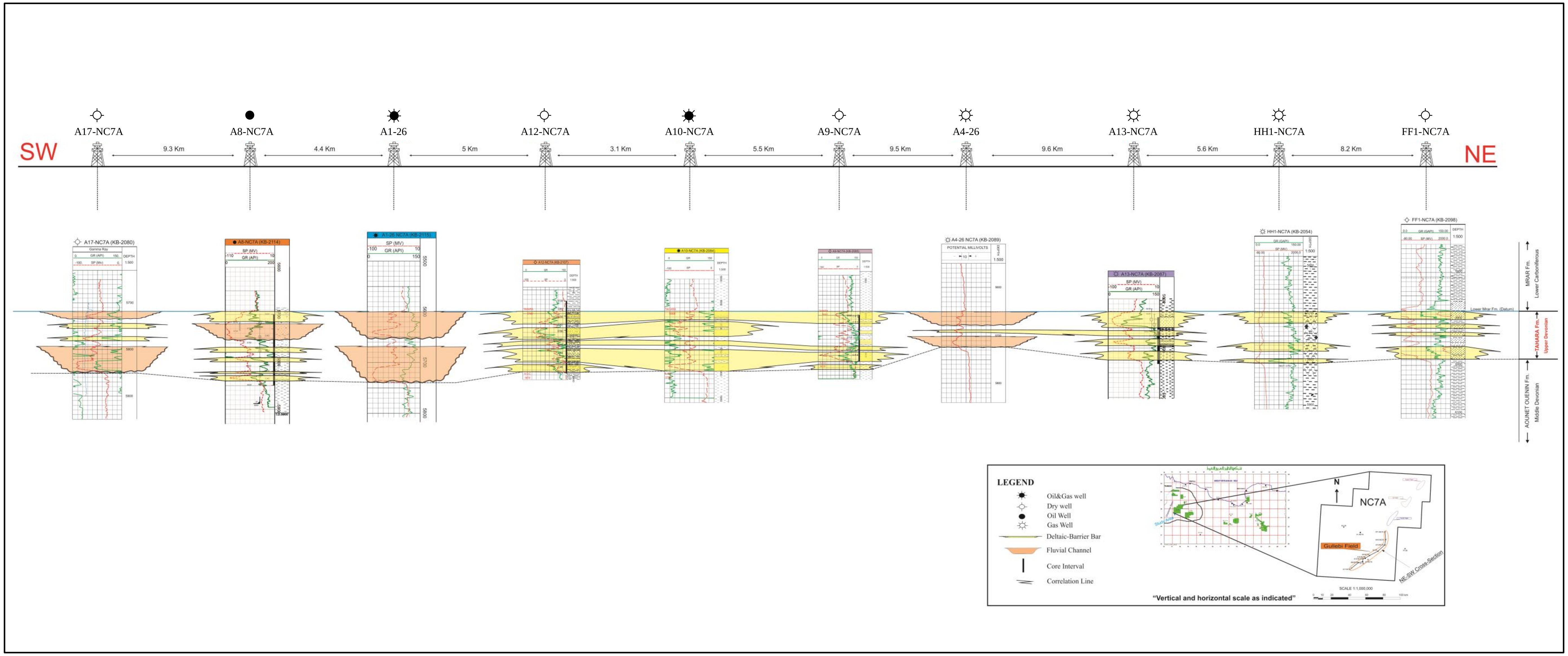


Figure 49. Stratigraphic cross-section across Gullebi Field, NE-SW direction (regional strike direction). (see Enclosure 1 for more details).

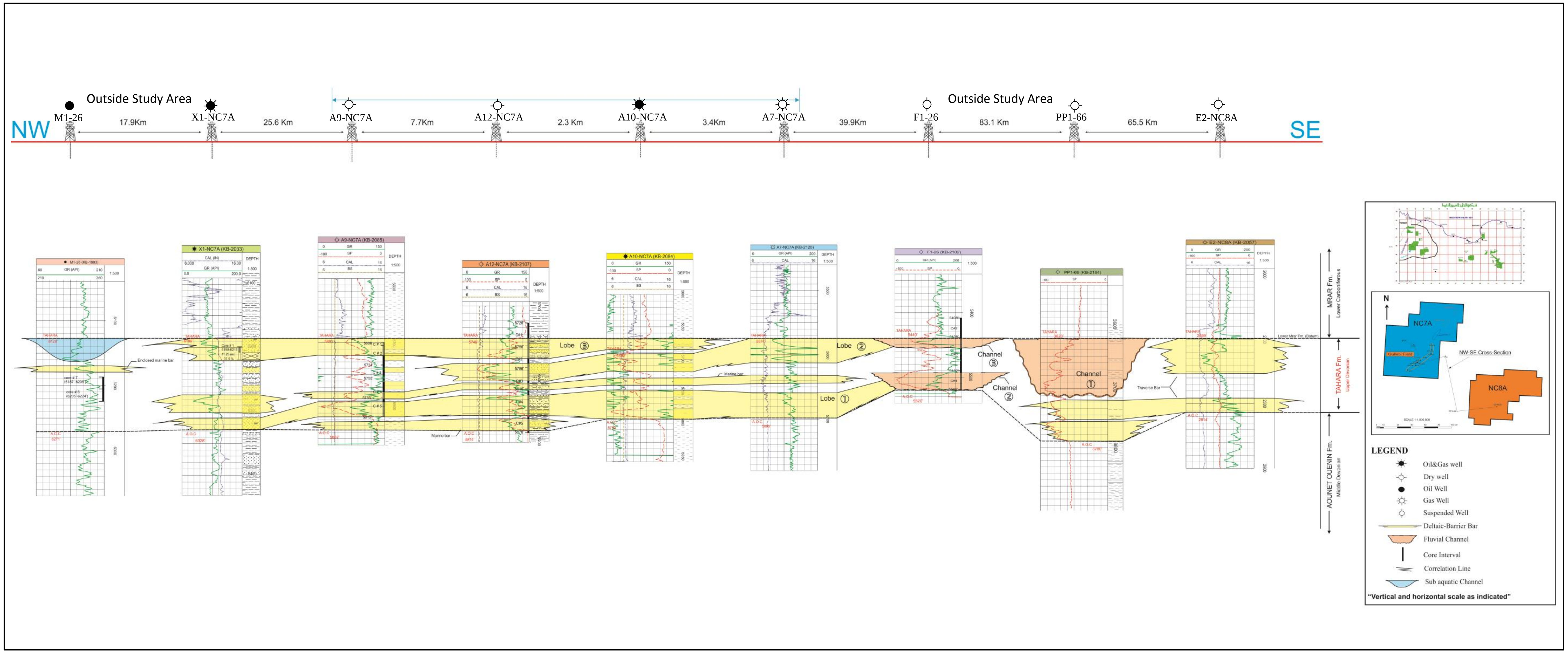


Figure 50. Stratigraphic cross-section in the NW-SE direction (regional dip direction). (see Enclosure 2 for more details)

7.2.2 Geological maps

7.2.2.1 Structure maps

Structure map (Fig. 51) on top of Tahara Formation was generated using well data (Table 6) of 49 wells from NC7A concession. The map was produced at sea level depth, the main fault zones of the Gullebi field which initiated by the major NE-SW trending fault (F1) have been plotted on this map after (Wonifaari, 2009). At least two southern associated faults "f2" and "f3" oriented NW-SE have been located on the Gullebi Field and plotted after (Teknica, 1997). The general picture of this map is showing that Tahara Formation representing high structural relief areas in the eastern side of the concession NC7A and gets low structural relief areas (deepening) toward the west, most of the wells in the eastern side of the concession where the main fields located were drilled on high structures within these areas. Two profile cross-sections were constructed on this map to imaging the paleo-relief (Fig. 51); the first A-A' was constructed on the strike direction and the second B-B' was constructed on the dip direction.

Another map for the Gullebi Field (Fig. 52), has been conducting by using seismic data (Teknica, 1997 and Wonifaari, 2009), in which Gullebi area is dominated by an elongate configured anticline trending NE-SW bounded on the SE flank by a major fault (F1). The wells of the Gullebi Field are located on this faulted anticline being positioned on the up-thrown block (hanging wall) of a large linear reverse fault (F1) which named Gullebi-Kabir Reverse Fault (GKRF). The fault (F1) takes a pronounced bend (change in direction) near the NE end of the Gullebi Field, in the area between wells A3-26 and A13-NC7A.

According to (Teknica, 1997), the anticline and the fault zone associated with this reverse fault appear to be deep rooted, with both being evident at Memouniat level and below and appear to persist upward throughout the entire sedimentary section. The displacement along the fault varies from SW to NE (ranges from 100 to 140ft), with the displacement generally diminishing to the NE. In addition, the vertical displacement evidenced across this fault zone appears to increase with depth, suggesting that the fault has been active over time. The anticlinal structure of the Gullebi Field is cut by at least two step faults (f2 & f3) (Figs. 51 and 52) where f2 is separating well A1-26 from well A5-26 with vertical displacement of about 50 feet, and f3 is separating wells A3-26 and A4-26 from the wells located to the SW and exhibiting vertical displacement of about 100 feet at AOB level and decreases upward to about 50-70 feet near Tahara level .

Table 6. Shows Aouinet Ouenine “C” and Tahara formations subsea depths “SSD” for selected studied wells in Gullebi Field, concession NC7A, Ghadames Basin.

Formation SSD / Wells	Aouinet Ouenine “C” Formation (ft)	Tahara Formation (ft)
A1-26	-3637	-3497
A3-26	-3541	-3451
A4-26	-3653	-3571
A5-26	-3688	-3552
A6-NC7A	-3632	-3486
A7-NC7A	-3574	-3468
A8-NC7A	-3739	-3592
A9-NC7A	-3752	-3608
A10-NC7A	-3710	-3584
A11-NC7A	-3673	-3533
A12-NC7A	-3788	-3659
A13-NC7A	-3648	-3550
A16-NC7A	-3739	-3609
A17-NC7A	-3769	-3637
A18-NC7A	-3687	-3550
A19-NC7A	-3518	-3440
A20-NC7A	-3556	-3424
AA2-NC7A	-3761	-3640
AA4-NC7A	-3768	-3663
AA10-NC7A	-3705	-3612
BB1-NC7A	-3796	-3705
C1-26	-4464	-4291
C1-NC7A	-3839	-3740
CC1-NC7A	-3826	-3719
CC2-NC7A	-3839	-3727
D1-NC7A	-3986	-3856
D2-NC7A	-4051	-3924
D3-NC7A	-4051	-3926
DD1-NC7A	-3878	-3744
EE1-NC7A	-3787	-3668
F1-NC7A	-4257	-4130
FF1-NC7A	-3892	-3786
GG1-NC7A	-3965	-3840
H1-NC7A	-4350	-4226
HH1-NC7A	-3754	-3643
II1-NC7A	-3524	-3426
M1-26	-4278	-4153
M2-NC7A	-4285	-4170
Q4-NC7A	-3868	-3760
Q8-NC7A	-3782	-3683
Q9-NC7A	-3812	-3709
Q10-NC7A	-3780	-3690
T3-NC7A	-3979	-3845
T4-NC7A	-3925	-3818
V2-NC7A	-3861	-3744
V3-NC7A	-3871	-3757
X1-NC7A	-4295	-4153
Y1-NC7A	-4393	-4238
Z1-NC7A	-3858	-3775

Other NW-SE step faults (f4 & f5) can also be seen outside the Gullebi Field along the NE extension of the major fault zone toward Al Kabir Field (Fig. 51).

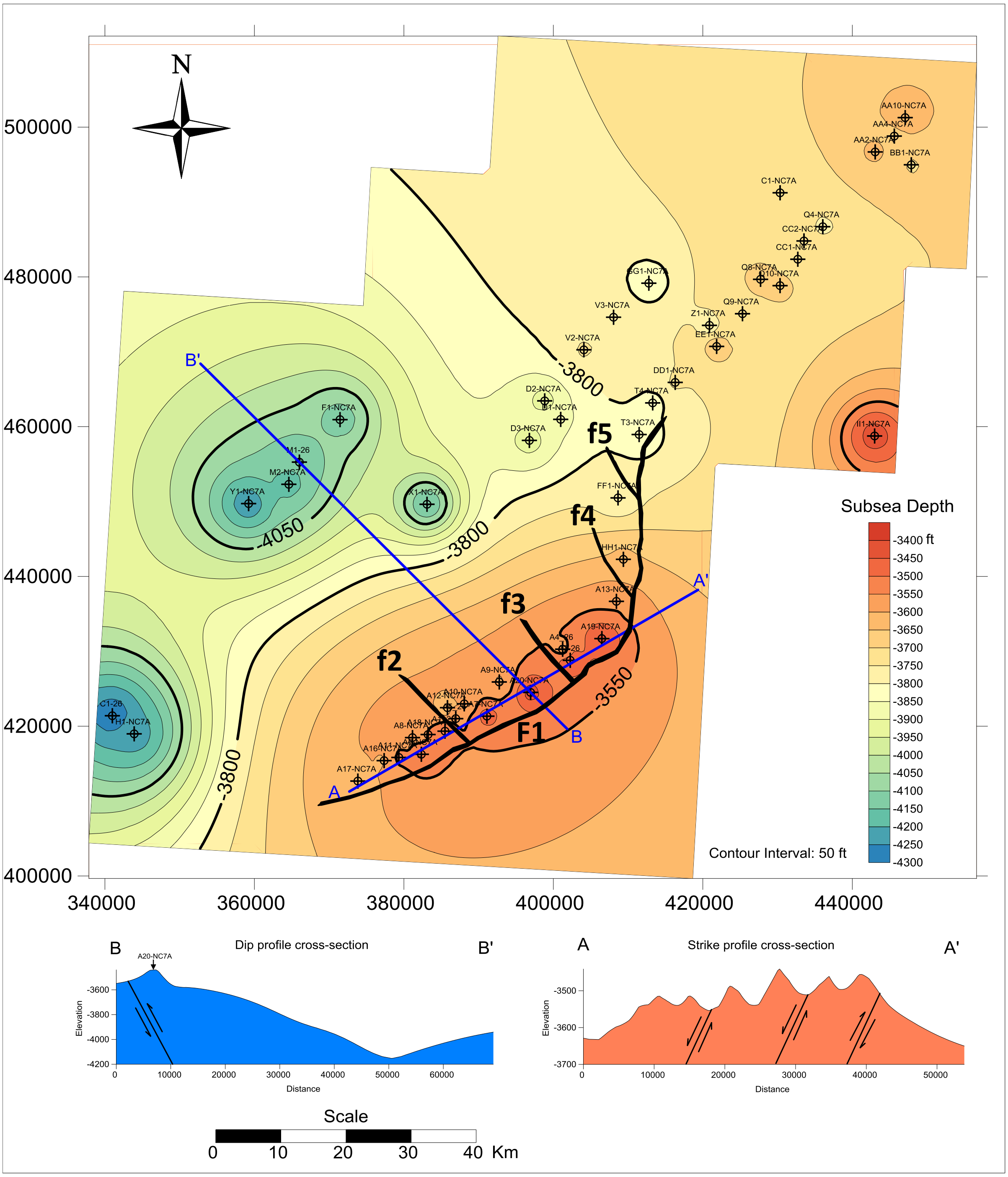


Figure 51. Depth structure contour map of Tahara Formation, concession NC7A, Ghadames Basin, with profile cross-sections A-A’ and B-B’. Note: NE-SW trending fault F1 and associated NW-SE step faults (f2-f5) (after Teknica, 1997).

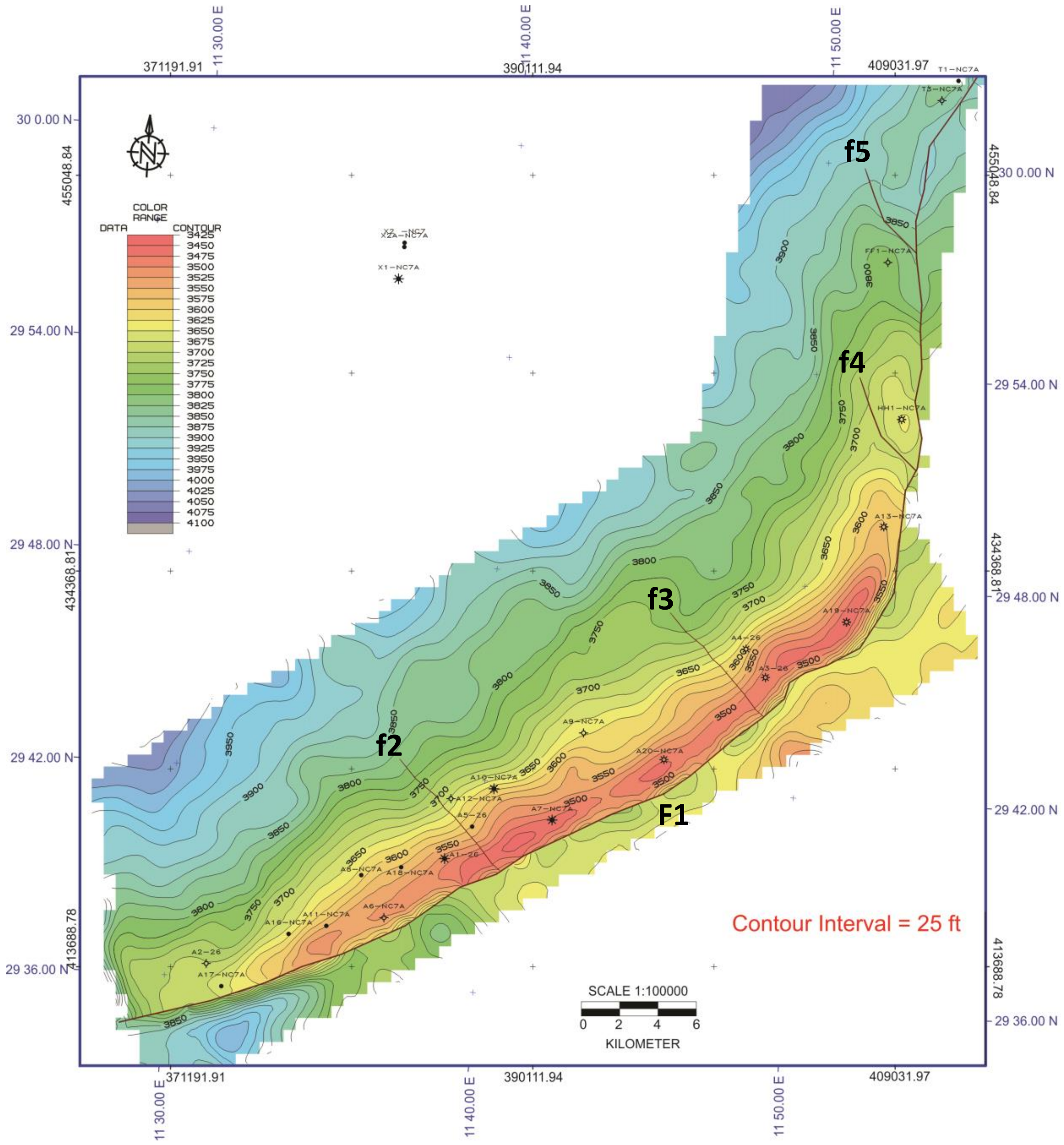


Figure 52. Depth structure contour map of Tahara Formation, Gullebi Field, concession NC7A, Ghadames Basin showing, NE-SW F1 major fault, f2 and f3 NW-SE step faults (modified after Teknica, 1997 and Wonifaari, 2009).

Two 3D subsurface structural models were generated by using (Surfer 12 software) on the top of Aouinet Ouenine “C” Formation (Fig. 53a) and top of Tahara Formation (Fig. 53b), showing pre-existed paleorelief areas on AOC level were imprinted and imaged on Tahara Formation level by sediments draping over paleohighs especially in the area of the Gullebi Field. Stacked model was generated for the two layers with contour line plotted over the Tahara layer surface (Fig. 54).

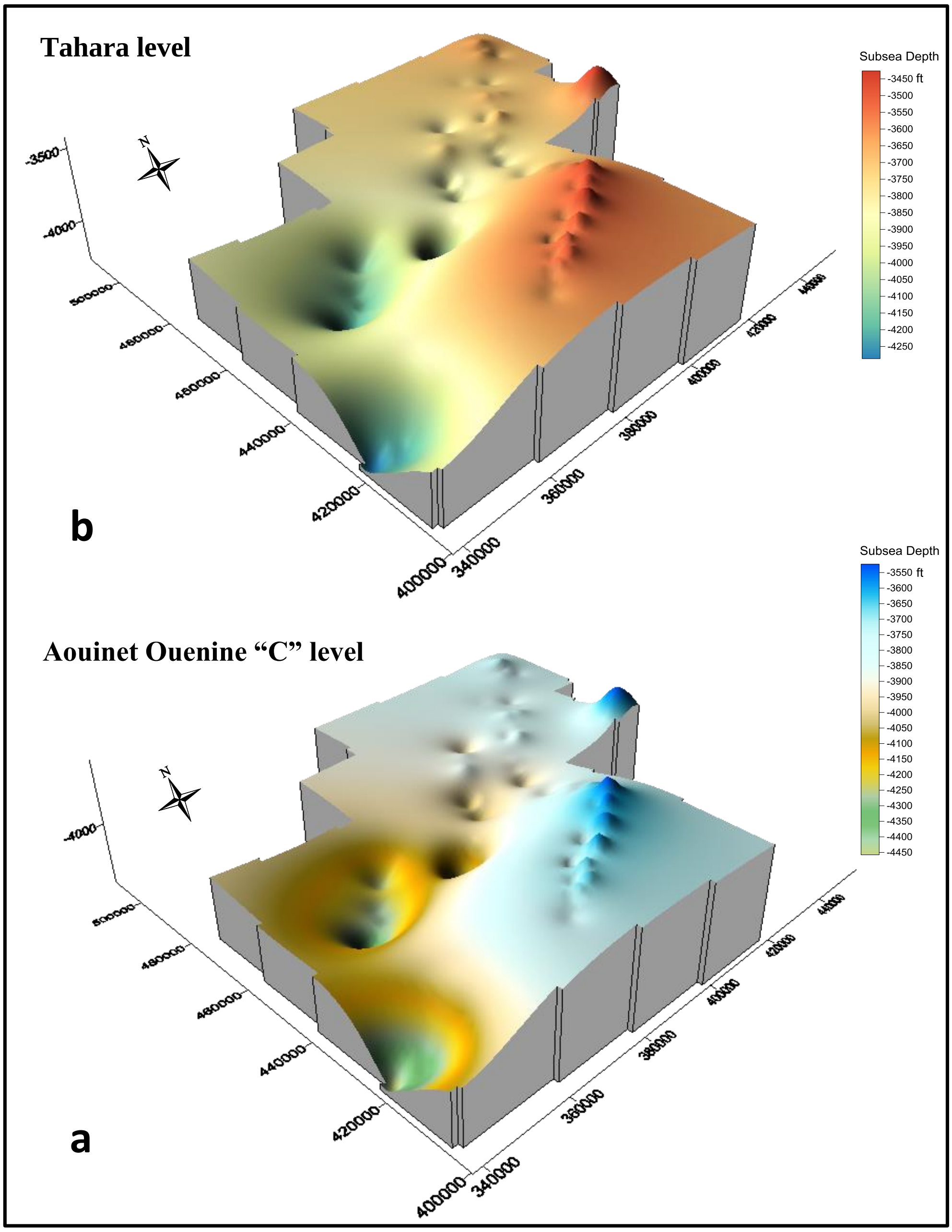


Figure 53. Three dimensional (3D) subsurface structural models on top of Aouinet Ouenine “C” Formation (a) and Tahara Formation (b), to visualizing subsurface paleo-relief of these formations in concession NC7A, Ghadames Basin, NW Libya.

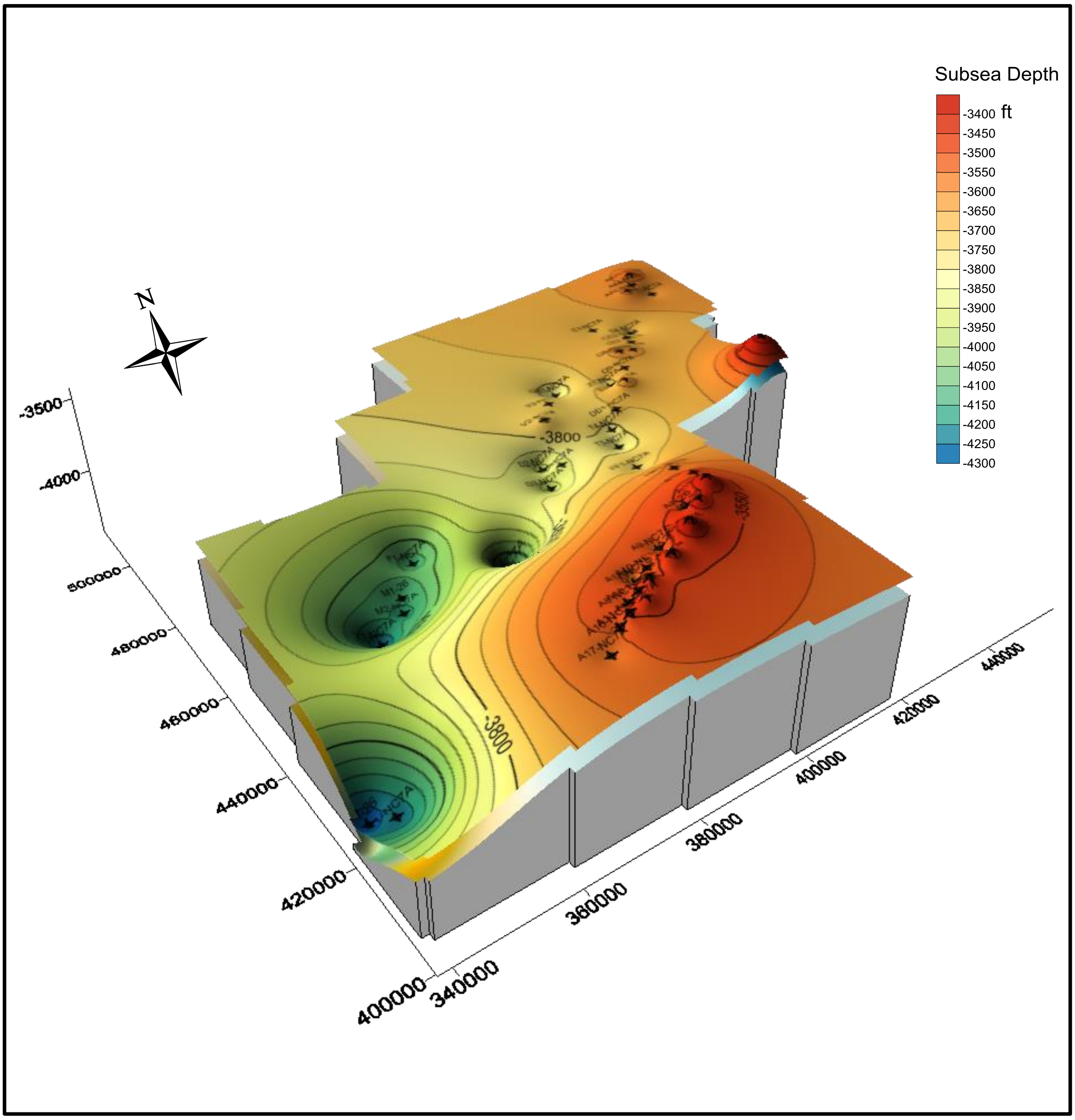


Figure 54. Stacked 3D model of Aouinet Ouenine "C" and Tahara Formations, showing paleo-relief and contour line variation from SSE high relief areas to NNW low relief areas, concession NC7A, Ghadames Basin, NW Libya.

NW-SE geo-seismic depth structural cross-section was constructed by (Beicip, 2011) crossing the Gullebi Field at well A20-NC7A (Fig. 55), illustrating the main reverse fault (F1) as it cuts through the various subsurface strata being drilled through this well. Fault displacement appeared to be maximum at Memouniat level and counts for about (300’) and minimum at Tahara level between (100’ to 150’)

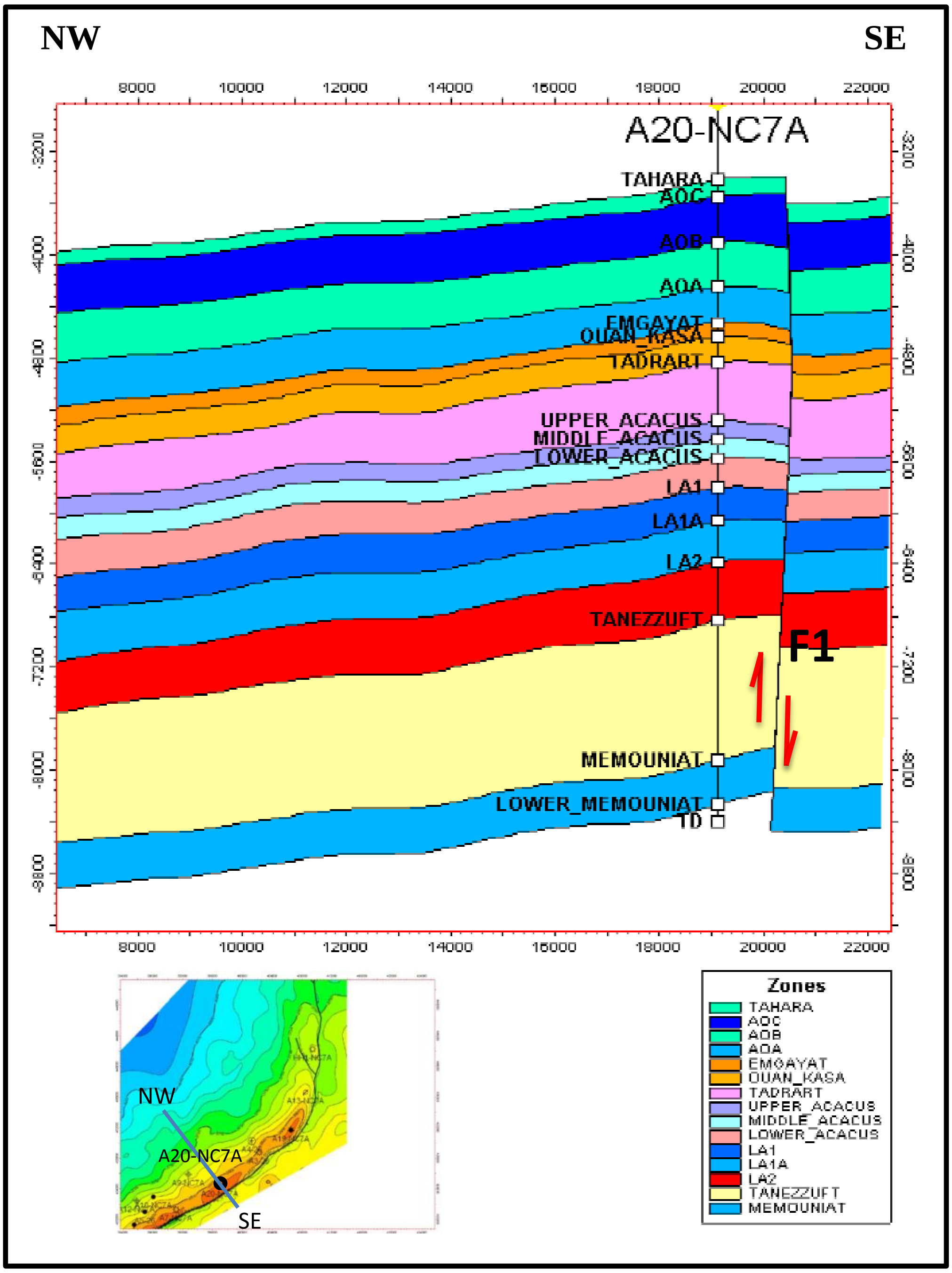


Figure 55. NW-SE geo-seismic depth structural cross-section, crossing the Gullebi Field at A20-NC7A well, concession NC7A, Ghadames Basin, (after Beicip, 2011).

7.2.2.2 Isopach maps

Measured total thickness (Table 7) of 49 wells were utilized to generate total isopach map of Tahara Formation, from which only 18 wells were used to map isopach maps of selected sandstone units in Tahara Formation in concession NC7A to show the regional Tahara Formation thickness distribution trends, paleorelief and to be used to define depositional history of the study area.

a. Isopach map of Tahara Formation

The total thickness map of the Tahara Formation (Fig. 56) in the study area (Gullebi Field) and the rest of concession NC7A reveals thickness variations range from 78ft to 173ft with an average value of about 125ft. It seems that the Gullebi Field structural trends and its extension to the NE direction has some influences on the Tahara thickness distribution. Gullebi Field trend is characterized by low and high relief areas through which thickness variations could be seen. A slightly more subsidence area is suggested by high contour values in the vicinity of wells C1-26 & Y1-NC7A to the southwestern direction.

Thereby the relative differences in Tahara Formation thickness between wells may be attributed to tectonic history of the area. As by the time of Tahara Formation deposition (Late Devonian) some differential subsidence and faulting have occurred, and subsequent Late Devonian sediments have been removed (reduced) partially by erosion.

Table 7. Shows thickness variations of Tahara Formation and the other selected units (upper sand unit for lower sequence and upper sand unit for upper sequence) for the studied wells in Gullebi Field, concession NC7A, Ghadames Basin.

(Note: (-) Indicates unused wells).

Wells / Formation thickness	Tahara Formation (ft)		
	Total thickness	**Upper sand unit for lower sequence**	**Upper sand unit for upper sequence**
A1-26	140	6	10
A3-26	90	-	-
A4-26	82	14	8
A5-26	136	-	-
A6-NC7A	146	-	-
A7-NC7A	106	13	9
A8-NC7A	147	6	13
A9-NC7A	144	12	12
A10-NC7A	126	11	13
A11-NC7A	140	-	-
A12-NC7A	129	7	20
A13-NC7A	98	10	4
A16-NC7A	130	-	-
A17-NC7A	132	7	7
A18-NC7A	137	-	-
A19-NC7A	78	-	-
A20-NC7A	132	-	-
AA2-NC7A	121	-	-
AA4-NC7A	105	-	-
AA10-NC7A	93	-	-
BB1-NC7A	91	-	-
C1-26	173	-	-
C1-NC7A	99	-	-
CC1-NC7A	107	-	-
CC2-NC7A	112	-	-
D1-NC7A	130	-	-
D2-NC7A	127	9	9
D3-NC7A	125	-	-
DD1-NC7A	134	-	-
EE1-NC7A	119	-	-
F1-NC7A	127	5	13
FF1-NC7A	104	8	12
GG1-NC7A	125	-	-
H1-NC7A	124	17	9
HH1-NC7A	111	10	14
II1-NC7A	98	-	-
M1-26	125	7	10
M2-NC7A	115	-	-
Q4-NC7A	108	-	-
Q8-NC7A	99	-	-
Q9-NC7A	103	-	-
Q10-NC7A	90	-	-
T3-NC7A	134	10	15
T4-NC7A	107	-	-
V2-NC7A	117	-	-
V3-NC7A	114	-	-
X1-NC7A	142	16	10
Y1-NC7A	155	10	21
Z1-NC7A	83	-	-

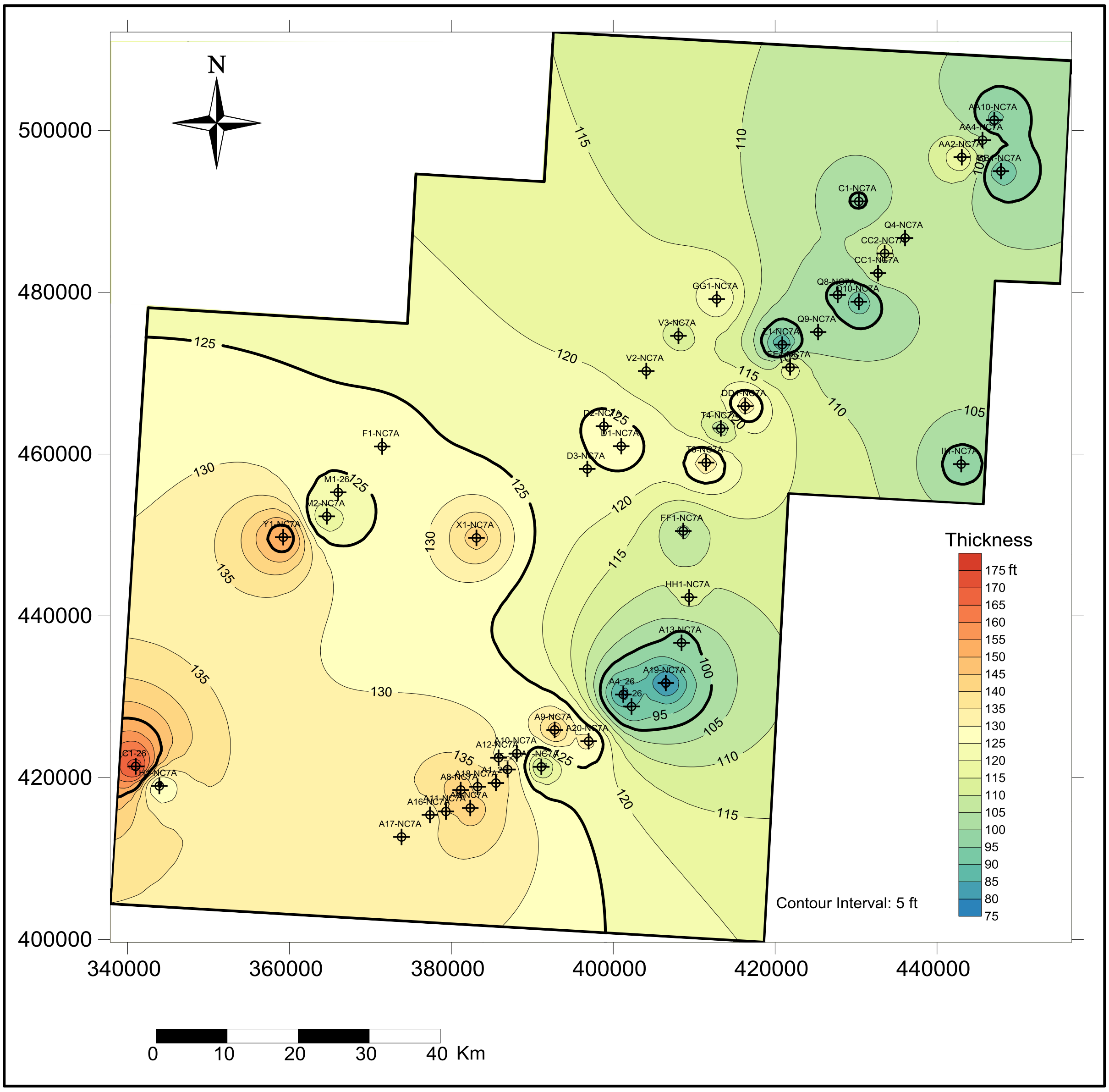


Figure 56. Isopach map of the Tahara Formation, concession NC7A, Ghadames Basin.

b. Isopach map of the upper sand unit of lower Tahara sequence

The upper sand unit of the lower sequence has a minimum thickness of about 5ft in the area of well **(**F1-NC7A**)** and a maximum thickness of about 17ft in the area of well **(**H1-NC7A**)** (Fig. 57). The isopach map showing some uniformity in sand unit thickness in the northern and southern areas of the Gullebi Field where the sand unit was not recovered with high thickness in these areas, while in the center of the field a considerable increase in thickness can be seen in the vicinity of well (A4-26 and A7-NC7A), with some reduction of thickness in the area of wells A9-NC7A, A10-NC7A and A13-NC7A. In the northwest and southwest of Gullebi Field in the areas of X1-NC7A and H1-NC7A the sand unit thickness was recovered with great thickness in these areas. Further in the northwest of the Gullebi Field and in the area of well F1-NC7A and M1-26 the sand unit thickness was reduced to the minimum especially in the area of F1-NC7A well, as it was replaced by marine basinal shale.

c. Isopach map of the upper sand unit of upper Tahara sequence

The upper sand unit has a minimum thickness of about 4ft in the area of well **(**A13-NC7A**)** and a maximum thickness of about 21ft in the area of well **(**Y1-NC7A**)** (Fig. 58). The northern and central areas of the Gullebi Field revealing the same tendency of thickness extending to the northwest in the area of Y1-NC7A with local thickness reduction in the area of wells A7-NC7A and A9-NC7A. In the vicinity of well A17-NC7A which represent the southern part of the Gullebi Field and the vicinity of A4-26 and A13-NC7A wells in the east, sand unit thickness reduction was observed.

By comparing the two isopach maps of Tahara units (Figs. 57 and 58), we observed that the sand units of Tahara Formation has different tendency where the upper sand unit of lower sequence had good sand thickness accumulation in the central of the Gullebi Field in well A4-26 and in the area of X1-NC7A in the northwest (represented relatively thicker trend) and H1-NC7A in the southwest. The great thickness of the upper sand unit of upper sequence was accumulated in the area of A12-NC7A in the center of Gullebi Field and in the further northwest of Gullebi Field in Y1-NC7A well (represented relatively thicker trend on this level).

In general, the accumulated thickness of both sand units is a function of available space to fill and paleorelief changes through time. So that the thickness of sand unit accumulated on a proximal deltaic surface has no relationship to the volume of sand unit or sediments being bypassed across it by channels. More important the degree of shallowing or deepening of the associated depositional surface. Sand units are thinning in either distal areas (marginal areas or distal deltaic areas) or laterally along coastal plains.Sand units are thinning in either distal areas (marginal areas or distal deltaic areas) or laterally along coastal plains.

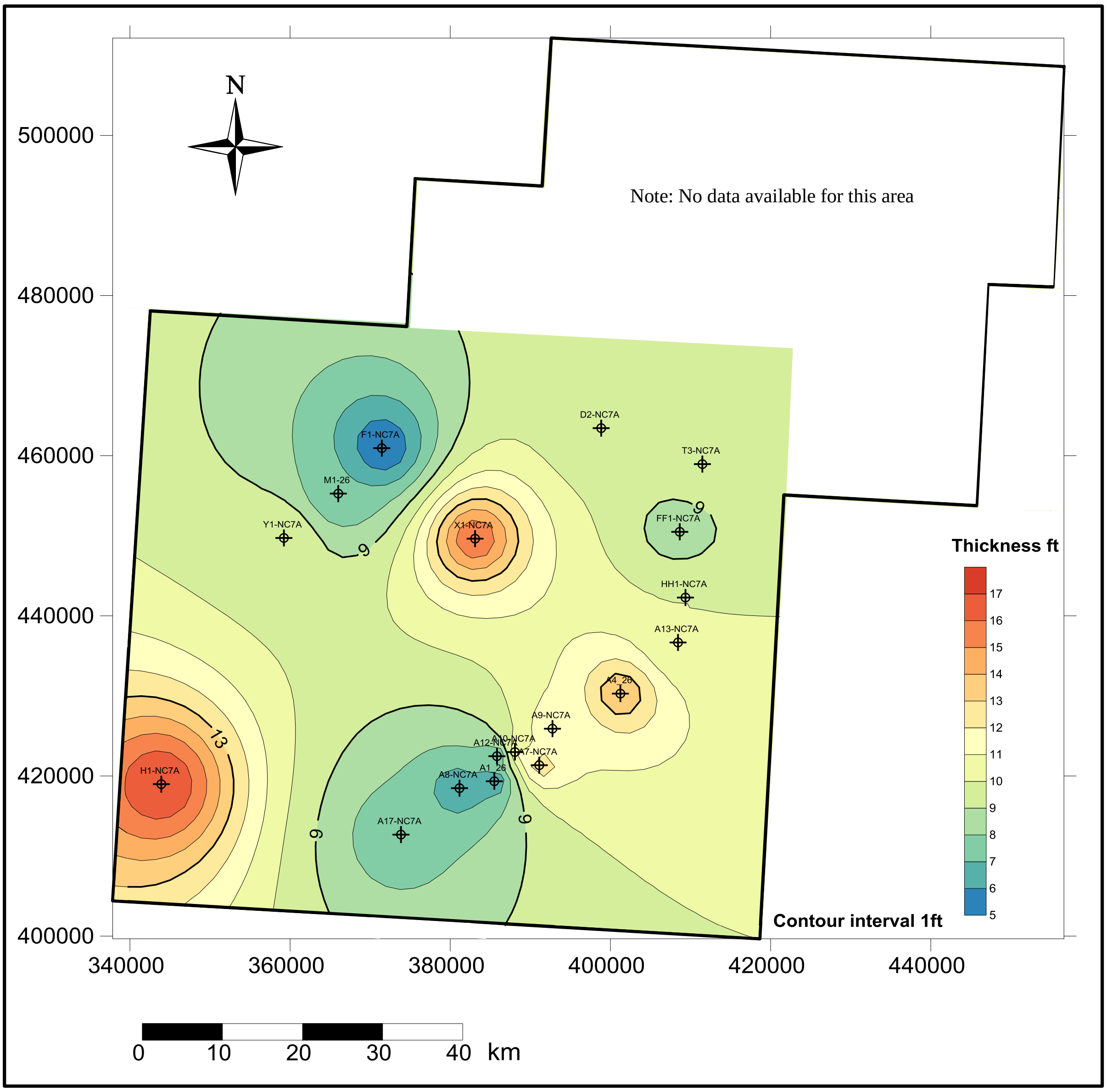


Figure 57. Isopach map of the upper sand unit of lower sand sequence of Tahara Formation, Gullebi Field, southern concession NC7A, Ghadames Basin.

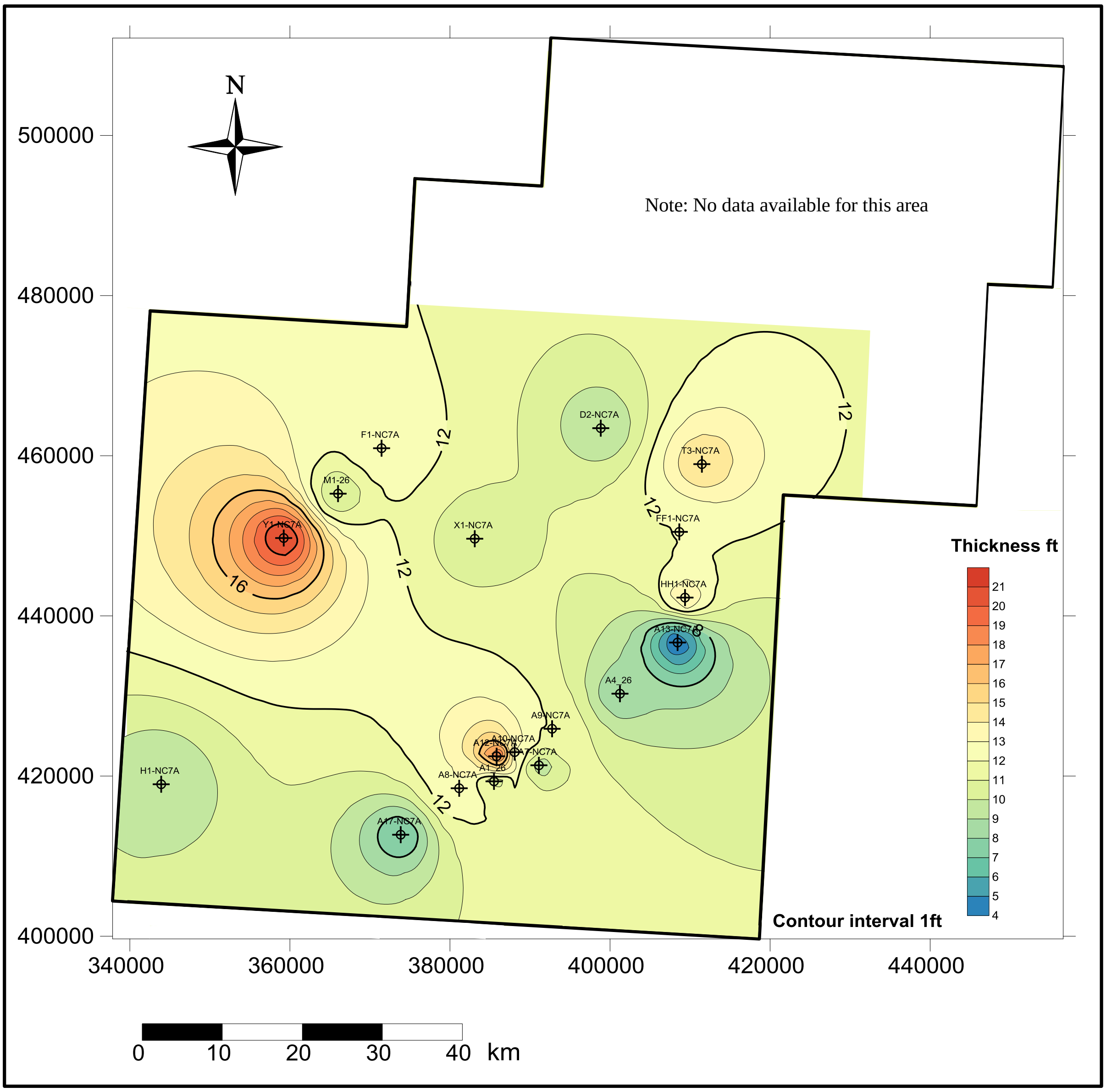


Figure 58. Isopach map of the upper sand unit of upper sand sequence of Tahara Formation, Gullebi Field, southern concession NC7A, Ghadames Basin.

7.2.2.3 Log facies maps

Log facies maps give a sense of the distribution, trends and internal sedimentary character of a reservoir interval (Shelton, 1971 in Shepherd, 2009). For each well, the gamma ray (GR) and/or spontaneous potential (SP) logs signatures of the upper sand units to the lower and upper sequences of Tahara Formation were selected, studied and plotted on a base map, then the various log patterns were mapped across the study area to define depositional boundaries related to the described lithofacies of Tahara Formation.

a. Log facies map of the upper sand unit of lower Tahara sequence

Figure 59 is a log facies map for the upper sand unit of lower Tahara sequence, showing the different lithofacies and their log shape characteristics. We could observe that most of the channel sands (coastal plain) are dominating the south and central parts of the Gullebi Field, also to the east of the concession NC7A which represented by F1-26 well. The mapping of this unit was also extended outside the study area (Gullebi Field) to cover the wells E2-NC8A and PP1-66 which showing coarsening upward GR curve revealing a southern-southeastern extension of beach-deltaic complex sediments in these vicinities. This log facies around wells E2-NC8A & PP1-66 extension was represented by dashed line to indicate limited data points and a wide spatial differences between the two wells and the study area.

From SSE to NNW arbitrary log facies boundaries were plotted to define the transition from coastal plain lithofacies of finning upward GR-signature to beach deltaic complex lithofacies characterized by coarsening upward GR-signature to eventually serrated to spiky GR-signature of basinal lithofacies. Laterally, across the Gullebi Field an alternating segments of finning upward GR-signature (in wells A17-NC7A, A1-26 and A4-26) with that of coarsening upward GR-signature (in wells A7-NC7A, A8-NC7A, A9-NC7A, A10-NC7A, A12-NC7A, A13-NC7A, HH1-NC7A and FF1-NC7A) are postulating possible shoreline (beach-deltaic sediments) incision by northwesterly prograded channel system.

The northwestern area of the concession with only one control point representing in the well M1-26, showing serrated to spiky pattern on GR curve of marine shale sequences shifted sandstone and suggested marginal or basinal deposits.

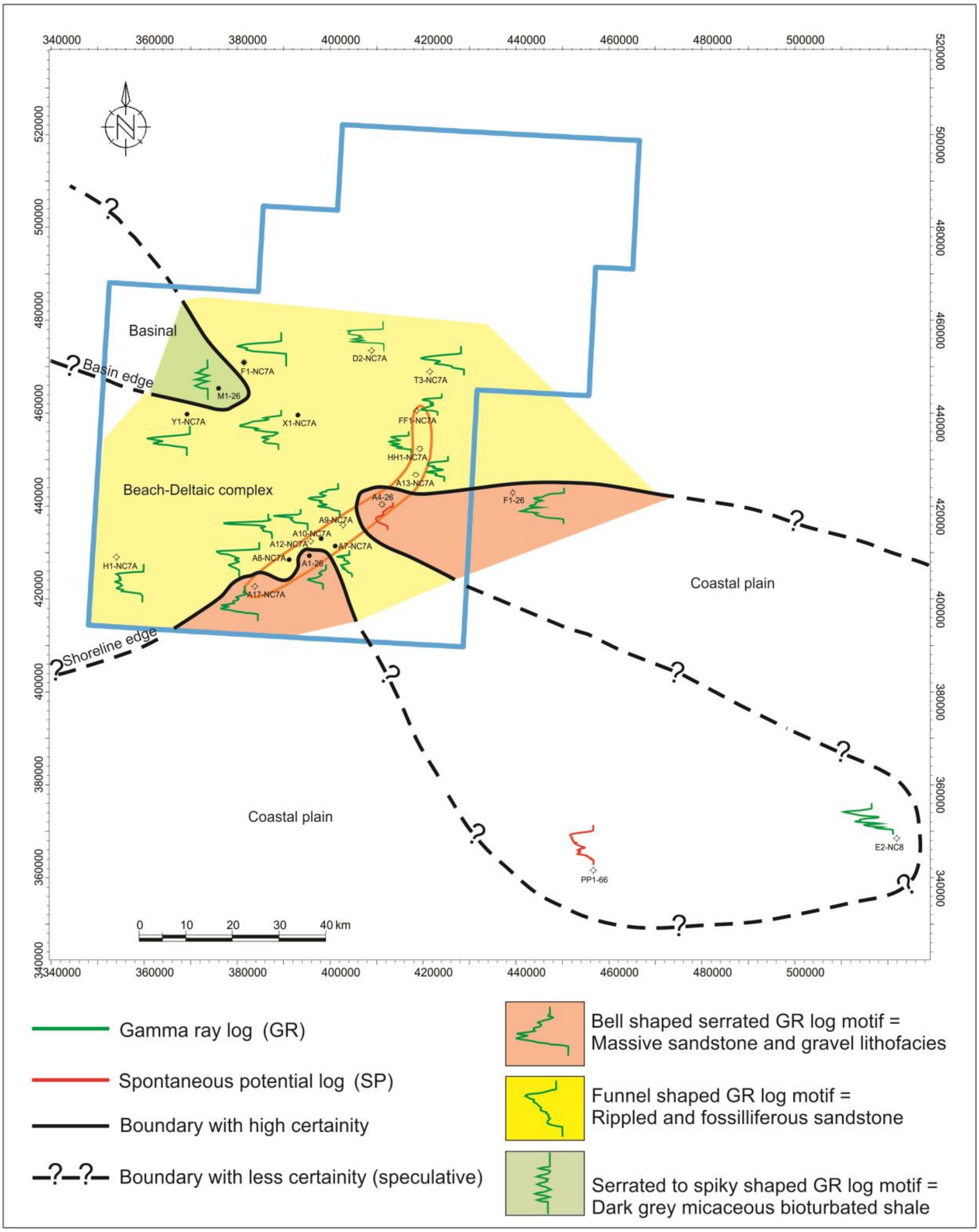


Figure 59. Log facies map of the upper sand unit of lower sand sequence of Tahara Formation, Gullebi Field, southern concession NC7A, Ghadames Basin.

b. Log facies map of the upper sand unit of upper Tahara sequence

The log facies map of the upper sand unit of upper sand sequence of Tahara Formation as shown in (Fig. 60), is revealing in general similar trend to the upper sand unit of lower sand sequence (Fig. 59). However, some local differences were encountered especially in well PP1-66 outside the study area in which a bell shaped SP curve is characterizing the upper sand unit suggesting prevailing prograded channel system that moved the proposed shoreline northward.

In the northwest of the Gullebi Field, the upper sand unit in the well M1-26 showing a small scale finning upward GR pattern rather than serrated to spiky pattern which was encountered in the upper sand unit of lower sand sequence (Fig. 59), which may suggest a possible subaquatic channel developed on a shelf slope area.

In summary, from both log facies maps (Figs. 59 and 60) the GR/SP motifs can easily define and respond to the representative lithofacies characterizing the studied units of the Tahara Formation. Sufficient close spaced well-logs data points like in the Gullebi Field permit lithofacies interpretation with certainty on the other hand, in sufficient wide spaced well control points as in the vicinity of wells PP1-66 & E2-NC8A (outside the study area) and farther north of well M1-26, will produce more speculative result and of less certainty.

By comparing isopach maps for the upper sandstone units of the lower and upper sand sequences with that log facies maps for the same sandstone units, it is inferred that the central and northern part of the Gullebi Field accommodated good sandstone thickness of beach-deltaic in origin which passes further northwest to open marine shelf and basinal area where the sandstone units pinched out to shale sequence.

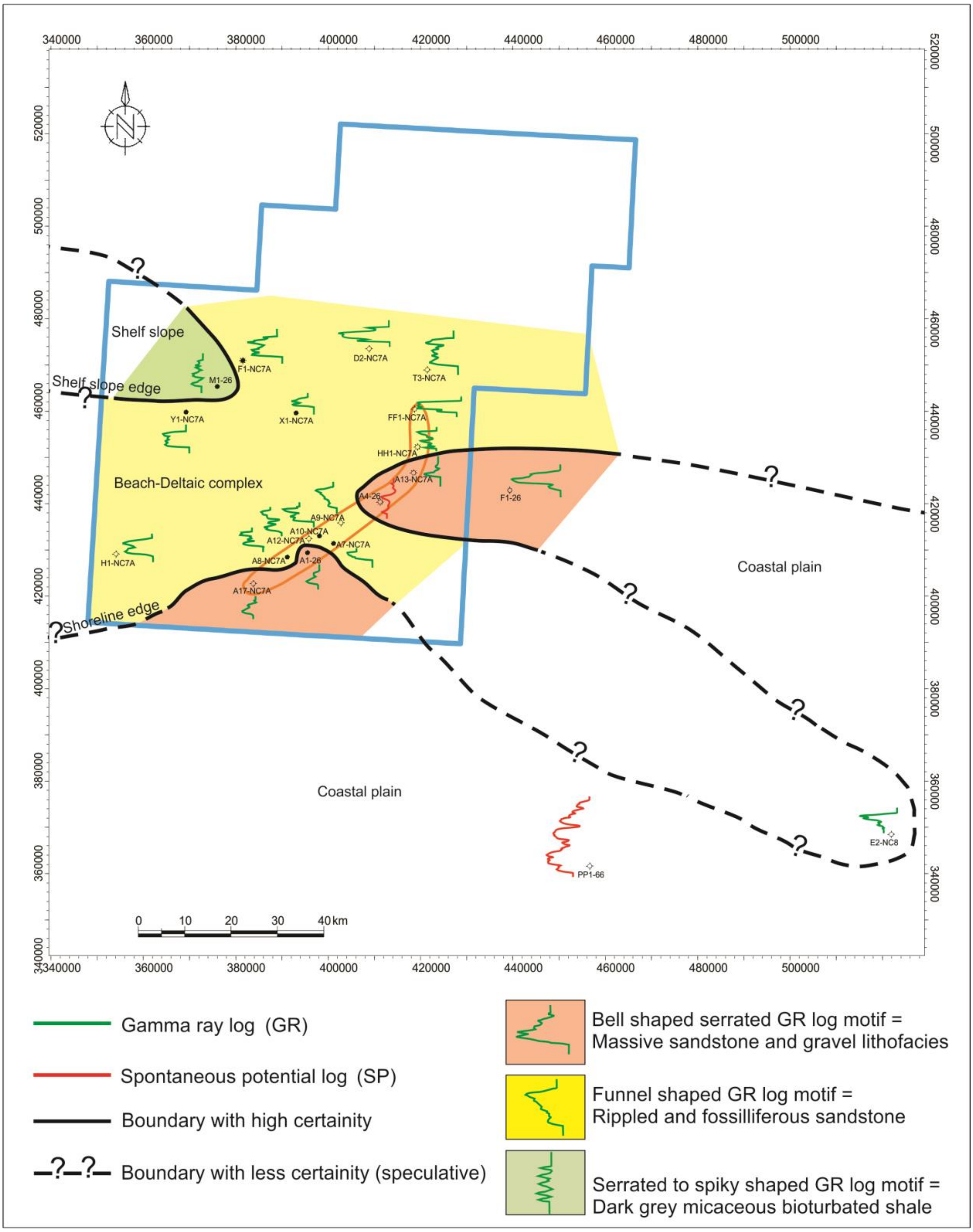


Figure 60. Log facies map of the upper sand unit of the upper sand sequence of Tahara Formation, Gullebi Field, southern concession NC7A, Ghadames Basin.

7.3 Depositional environment model for Tahara Formation

Depositional environment model (Fig. 61) for the studied Tahara Formation in Gullebi Field, may be inferred by gathering multidisciplinary data to illustrate flow of lithofacies change posulating paleo-depositional history framework for the area in question.

The Late Devonian Tahara Formation in the Gullebi Field, concession NC7A of Ghadames Basin, is dominated by fine-very fine cross laminated and rippled sublithic-quartzarenitic sandstone with some silty shale interbeds and ferruginous beds with some thin beds of conglomerate contain plant materials and brachiopods fragments. On the basis of GR-log signature, this formation is composed of two coarsening upward sequences (lower sand sequence and upper sand sequence) (Figs 48 and 50). The lower sand sequence rists on lower compacted marine shale (marine shelf-basinal shale) deposited during early transgressive phase before the deposition of Tahara sandstones.

The marine shale was overlained by fluvial deposits in the SE direction of Gullebi Field at the vicinity of wells PP1-66 and F1-26, these fluvial deposits characterized by conglomeritic scoured surface and rip-up reddish muddy clasts indicating channelized current. Some thin scattered iron-rich units were interrupted the sequence locally at wells A8-NC7A, A9-NC7A, A12-NC7A and A13-NC7A which indicate local lagoonal lithofacies which is evident by the lack of open marine biota and the abundance of deep bioturbated reddish muddy lithofacies suggesting deposition in protected area. Occasionally these burrows filled by silt and very fine sands. The fluvial system or channels prograded NW crossing the Gullebi Field which characterized by shoreline dominated sediments from beach sand to deltaic in origin as inferred by their cross lamination, rippled structures and hummocky cross stratification.

The upper sand sequences is formed by the repetition of overlapping depositional events where the sand body again overlies basinal marine shale and record another progradational package as channels fill the lower topography in SE leading to more coastal-deltaic (shoreface) deposits to more further laterally basinal marine reworked sand and marine silts/shale to the NW.

The Tahara Formation provides a unique opportunity to study a delta system which built into a slowly subsiding basin and progressively changed from being fluvial to beach-deltaic sand to eventually marine sand, silt and shale. It is therefore considered to provide a valuable depositional model (Fig. 61) for deltaic system developed on relatively stable cratonic Ghadames Basin.

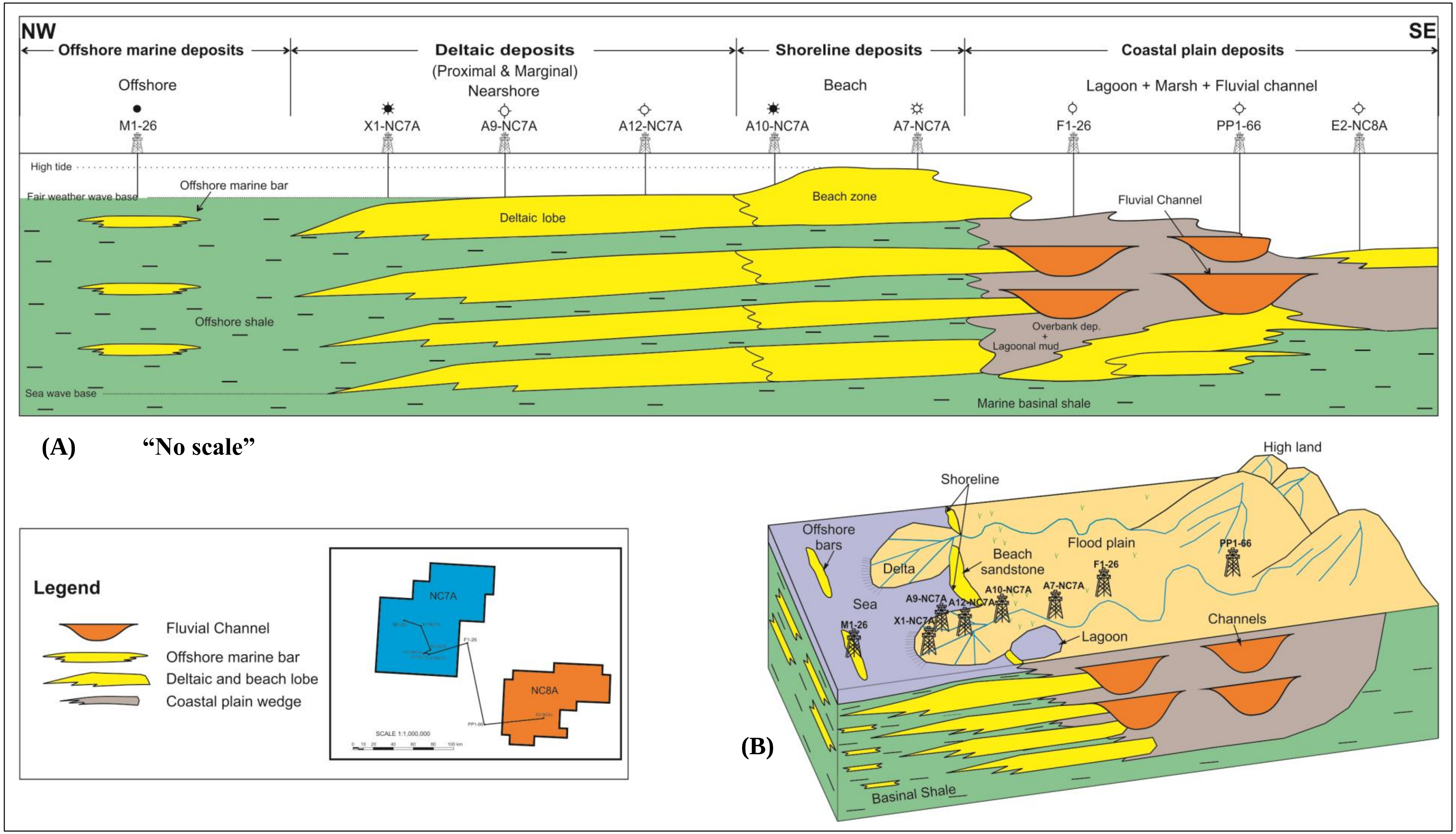


Figure 61. Depositional model of Tahara Formation, **(A)** Based on stratigraphic cross section (Fig. 50), **(B)** Hypothetical block diagram, Gullebi Field, Concession NC7A, Ghadames Basin.

Chapter (8)

Stratigraphic and Structural Factors Controlling the Tahara Sandstone Reservoir Development in Gullebi Oil Field

The main aim of this chapter is to identify the stratigraphic and structural factors controlling the Tahara sandstone deposition and development in the study area (Gullebi Field).

8.1 Stratigraphic factors

The Late Devonian section at the Gullebi Field typifies the occurrences of the Tahara Formation which a basal part (lower sand sequence) dominated by sand and shale units averaging about 43 feet in thickness, and the upper part (upper sand sequence) is dominated by sand and shale units averaging about 44 feet in thickness. The Tahara Formation is further subdivided into seven (7) lithofacies including:

(1) Dark grey micaceous bioturbated shale.

(2) Parallel laminated silty sandstone and silty shale.

(3) Varicoloured silty shale and bioturbated iron-rich shale.

(4) Bioturbated sand and shale.

(5) Interlaminated shale and silty sandstone.

(6) Massive sandstone and gravel.

(7) Rippled and fossilliferous sandstone.

By observing the total thickness distribution of the Tahara Formation (Fig. 56) and of some selected sandstone units of the studied Gullebi Field (Figs. 57 and 58), generally, the distribution of thicknesses in the Gullebi Field is showing remarkable thinning of the sandstone units in the lower and upper sequences toward the northeast. The area in the northeast is represented by HH1-NC7A and FF1-NC7A wells, supposed to accumulate huge thickness of deposits according to their depths. We believe that this area may have been located on locally high topographic area at the depositional time, so did not receive much sediments.

In contrast, in the western part of the Gullebi Field at the vicinity of C1-26 and H1-NC7A wells, thick sandstone units of both sequences were encountered (Fig. 56) as these localities characterized by structural low areas. The Tahara Formation and its lithofacies patterns are recognized that can be ascribed to geographic or stratigraphic architecture controls.

Stratigraphic factors related to sea level changes reflected on depositional lithofacies types and sedimentation rates (thickness variations). The sea level fluctuations, especially at the depositional time of the upper Tahara sandstone may be related to tectonic movement, whereas Beciep (1972) suggested that epirogenic oscillations, although weak, affecting the shallow marine basin inherited of the Late Devonian times, produced frequent facies changes and stratigraphic gaps.

Whatever their causes, variations of sea level have profound repercussions, especially on the continental margins, although the shifts of paleoshorelines are generally due more to local or regional deformation of the cratonic margin than to eustatic fluctuations. Drowning terrestrial topography, and especially the low-lying valleys, a marine transgression creates an incised coastline with isolated islands. Regressions are characterized by smoother coastlines. The degree of emersion of the continent controls the base level of the fluvial system, and, therefore, the interplay of erosion and sedimentation, both continental and marine. A high sea level decreases erosion in the low fluvial valleys and increases the sedimentation on the continental shelf; a low sea level causes erosion of the shelf and the terrigenous products are transferred directly to the base of the slope, where they accumulate as deltas, submarine (offshore) bars or may reach as far as the abyssal plain (Fig. 62). An eustatic rise creates new communications by drowning topographic high areas. It therefore facilitates interprovincial exchanges and cause the development of transgressive sediments of shallow marine environment. An eustatic drop tends on the contrary to isolate basins from each other and may cause the development of regressive sediments of restricted, brackish or hypersaline environments (Cotillon, 1992).

Other stratigraphic factors are better explained by the characteristics mineralogic composition of the studied sandstone units and the differences in diagenetic processes (compaction, cementation and dissolution). Sublitharenite to quartzarenite is the major mineralogical framework of the Tahara Formation in Gullebi Field (Fig. 27) with some extends to subarkosic and litharenite influences. This variation in compositional pathways may reveal some heterogeneity throughout the studied area; from sublitharenite in rippled and fossiliferous sandstone lithofacies (beach to proximal deltaic) in wells A8-NC7A&A12-NC7A characterized by partial calcite cementation and of partial dissolution of feldspar grains representing high quality sandstone with total porosity of (20%) and of measured log permeability (36md), to sublitharenite-quartzarenite, grain supported sandstone in massive sandstone and gravel lithofacies (fluvial channel) of A8-NC7A and F1-26 wells with degree of high silicate and partial calcite cementation and of less clay contents reveal more mature sandstone of medium-quality with intermediate porosity (12%) and of measured log permeability (7md). However, subarkosic to litharenite interlaminated shale & silty sandstone lithofacies (marginal deltaic) of A8-NC7A and A12-NC7A wells with very fine grained, highly cemented and of pore-clogging clay, reveal their immaturity and of less sandstone quality as of lowest porosity (10%) and measured log permeability (4md). Therefore, the Tahara sandstone quality and its reservoir development can be predicted by using lithofacies and their depositional environments.

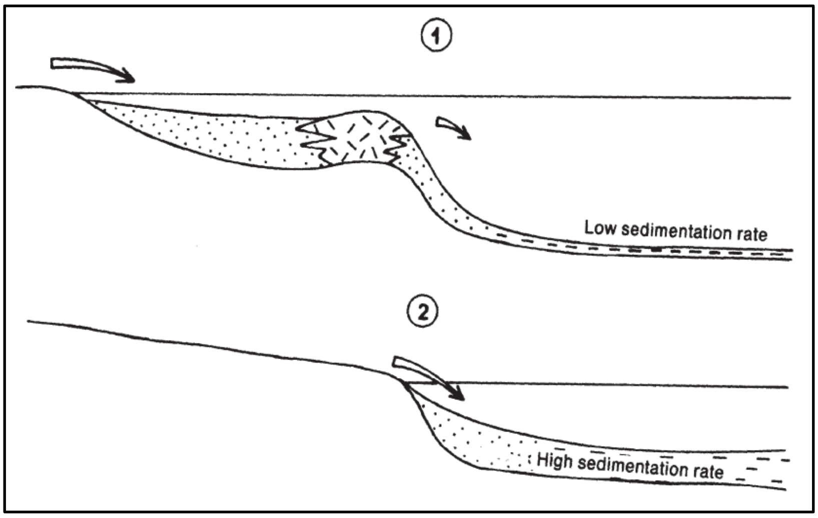


Figure 62. Influence of eustacy on oceanic detrital sedimentation. (1) High sea level; (2) low sea level (after Cotillon, 1992).

8.2 Structural factors

The Gullebi Field is located in the southern edge of concession NC7A in the south central part of the Ghadames Basin (Fig. 1). General reservoir characteristics are given in table (8). The field is developed along an anticlinal ridge that trends NE-SW (Fig. 52) and composed of chain of at least 4 isolated culminations. This anticlinal ridge is considered to be as a part of a series of anticlinal structures and associated high-angle faults, with prevailing compressional movements diffused in the Ghadames Basin (Maria, 1991). This trended structure has a significant impact on the depositional history of the Tahara sandstone. In fact it is not clear if these highs belong to real deformation (folding) to the Devonian rocks. However, it is believed that these anticlinal structures were resulted from moulding and draping of overlying strata on top of pre-existing basement blocks (Beciep,1972). Depth structure map on top of Silurian Tanezuft Formation in Gullebi Field (Fig. 63) shows the impact of the paleo structural highs on this formation which reached and imprinted on the top of Late Devonian Tahara Formation (Fig. 52).

Therefore, paleostructural factors or structural configuration of the Gullebi Field (Fig. 64) during and since the time of deposition of Tahara Formation was controlling the pattern of its sandstone and their development at some localities (e.g. A1-26 well is located at top of structural high, is characterized by thick sandstone sequences and some shale with fair-good porosity, where A9-NC7A well is located at relatively low structure is characterized by having less sandstone sequences and more shale contents with relatively poor porosity.

Table.(8) General characteristics and volumetric of the Tahara sandstone in Gullebi Field. (* data was extracted from Teknica Exploitation Evaluation Study (1997), on Gullebi Field, concession NC7A.

Current Operator	Arabian Gulf Oil Company	**Hydrocarbon sources**	Tanezzuft and Aouinet Ouenine "C" formations
Discovery Date	Oasis 1959 A1-26 well	**Productivity unit lithology**	Sandstone
Average Depth of reservoir sandstone	5657/-3566ft	**Oil water contact "OWC"**	U.Sst. U.Seq. -3599ft U.Sst. L.Seq. -3676ft
Average structural area (acres)	117 078.53	**Average gross pay**	U.Sst. U.Seq. 22ft U.Sst. L.Seq. 18ft
Top seal	Mrar Formation	**Average net pay**	U.Sst. U.Seq. 11ft U.Sst. L.Seq. 9ft
Bottom Seal	Aouinet Ouenine "C" Formation	**Average porosity "Ø" %**	14%
Trap type	Faulted Anticline "structural trap"	**Average permeability "K" (md)**	16 md
***Water Saturation S_w**	22.5%	***Formation volume factor "F.V.F"**	Bo 1.57 rb/stb Bg 1.195 rcf/scf
***Water Salinity**	Ranges from 51.000-115.000 ppm	***OOIP (MMSTB)**	245
***Oil Gravity "API"**	41.5	***OGIP (Bscf)**	1054
***Bottom hole Temp. BHT**	180 °F (82 °C)	***Reservoir Pressure psi**	2150 psi

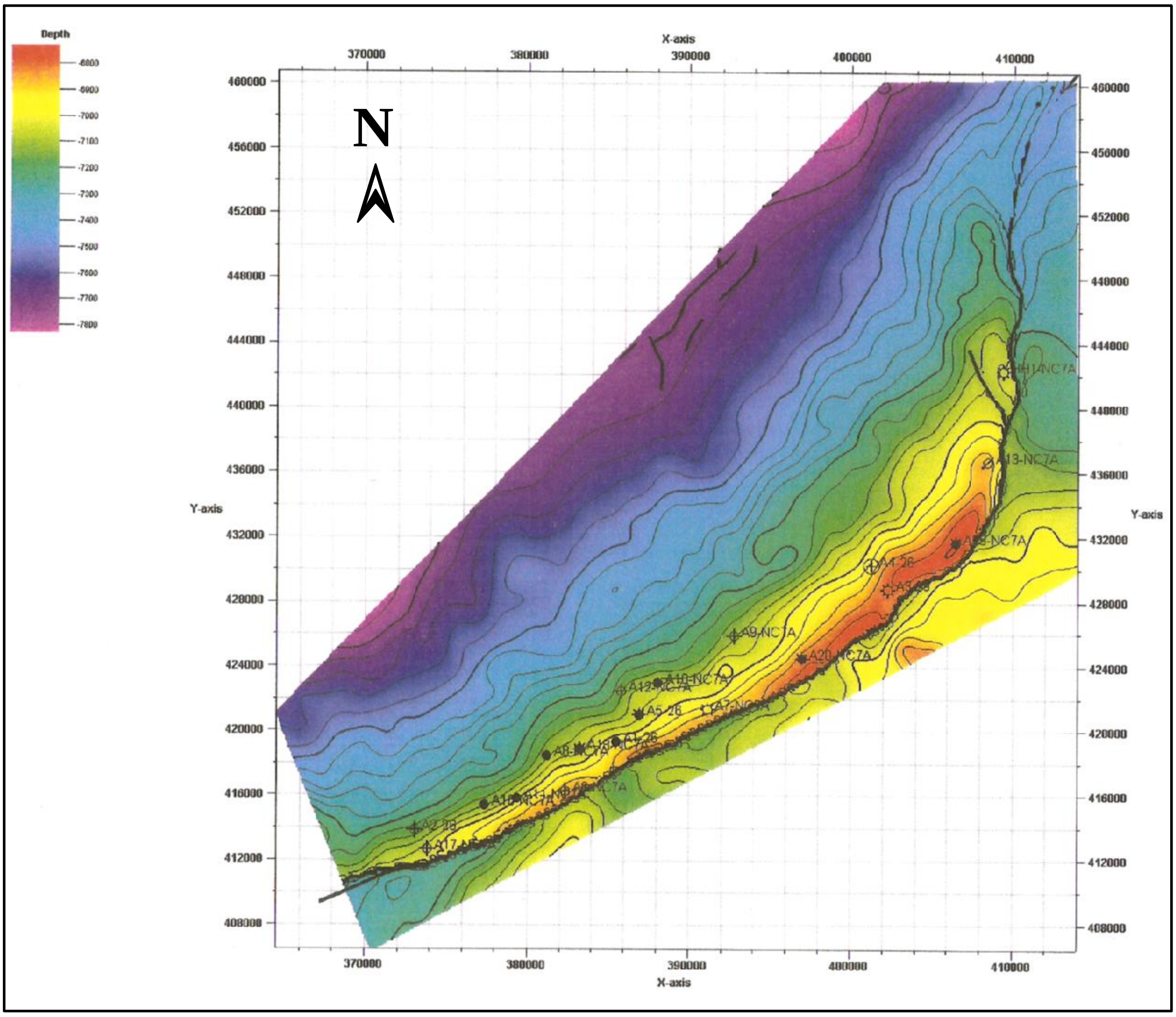


Figure 63. Depth structure contour map on top of Tanezuft Formation, Gullebi Field, concession NC7A, Ghadames Basin (after Beicip, 2011).

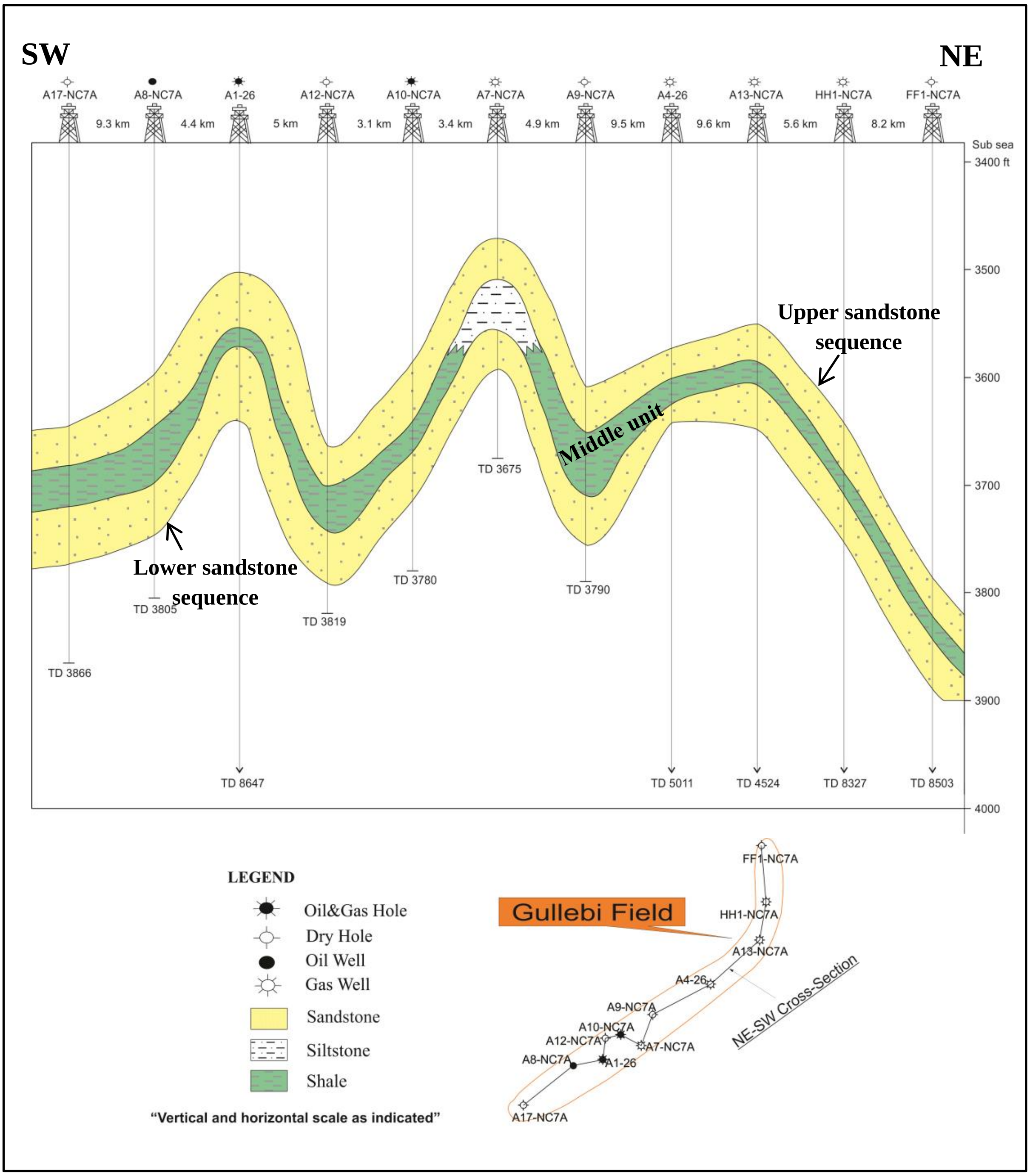


Figure 64. NE-SW structural cross section through Gullebi Field shows the structural configuration characterizing of the Tahara Formation, concession NC7A, Ghadames Basin.

Major NE-SW striking bounding fault parallel to the axial plane of the anticlinal ridge along its NE side (Fig. 52), with vertical offset of as much as (50 feet) is present through the Tahara reservoir sandstone as it has been shown to be at least locally sealing (Fig. 55). The

Tahara Formation is underlain by shale of Aouinet Ouenine “C” Formation and overlain by shale of Mrar Formation (Fig. 8), an up dip truncation of Tahara sandstone is existed along sealing fault in the vicinity of well A20-NC7A (Fig. 55) enhancing productivity in the location.

At least three associated step faults were observed in the southern and central Gullebi Field (Figs. 51 and 52) which oriented NW-SE and downdip to the south (Teknica, 1997), if these faults were pre-syndeposition of Tahara Formation thus it may explain the increasing of thickness in the south of the Gullebi Field. Similar oil/water contacts obtained from petrophysical analysis and well test results (Teknica, 1997), of some wells located southerly and northerly to the NW-SE striking fault (f2) have revealed the less effectiveness of this fault as oil/water contact is continued between different sandstone reservoirs.

The presence of faulting has exploration implication for Tahara sandstone reservoirs in Gullebi Field. So that, structural cross-sections and structural maps are good avenues to target Tahara plays from a structural basis rather than only stratigraphic basis. In addition, to using traditional isopach maps to delineate thicker Tahara sections, mapping the fault network (NE-SW&NW-SE trended faults) can add additional confidence for exploration and development.

Generally, the production is confined to sandstone zones of (upper sandstone sequence) having fractured reservoirs presumably in the vicinity of wells A7-NC7A, A13-NC7A, A17-NC7A, A18-NC7A and A20-NC7A. The main through going major NE-SW fault in the southeastern portion of the Gullebi Field could provide for increased fractures in sandstone levels and conduits for fluid flow for more precipitation in these sandstones.

As a result, combination of both stratigraphic and structural factors are influencing the development of reservoirs of Tahara Formation.

Conclusions

This comprehensive study of the Tahara Formation of the Gullebi Field, concession NC7A in Ghadames Basin, NW Libya has produced several conclusions. These are:

1. Seven lithofacies identified in the cores of the Tahara sandstones in the Gullebi Field represent (i) Dark grey micaceous bioturbated shale (offshore-basinal marine), (ii) Parallel laminated silty sandstone and silty shale (proximal deltaic), (iii) Varicoloured silty shale and bioturbated iron-rich shale (lagoon), (iv) Bioturbated sand and shale (beach), (v) Interlaminated shale and silty sandstone (marginal deltaic), (vi) Massive sandstone and gravel (fluvial channel) and (vii) Rippled and fossilliferous sandstone (beach). These lithofacies are composing two sand sequences (lower and upper) of the Tahara Formation which bounded on the top and bottom by marine shales.
2. Conventional wireline logs, whole cores and stratigraphic cross-sections created from them, support the fluvial, transitional (beach and deltaic) and marine model.
3. Petrographic observation of some selected sandstones have revealed that these sandstones are sublitharenite to quartzarenite, with few samples of litharenite and subarkose texture. The principal cements occluding porosity include silica cement (through pressure solution and quartz overgrowth), carbonate cement (calcite) and clay cement (pore filling kaolinite) and partially clay matrix (illite).
4. The Tahara sandstones show a variety of diagenetic phases where the mechanical and chemical compactions playing important role. Since the depositional texture does not vary significantly between studies sandstone units, the 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. 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.
5. Three reservoir lithofacies associations in the Tahara sandstones were defined based on different compositions and diagenetic patterns, represent different reservoir qualities: good quality lithofacies, medium quality lithofacies and low-quality lithofacies. Overall

reservoirs have low-quality; however, they are interspersed with medium- and good-quality levels.

6. linking diagenesis to the different depositional environments such as fluvial, transitional and shallow marine of the Tahara sediments has important implications for predicting the spatial and temporal distribution of diagenetic alterations and their influence on reservoir quality.
7. Isopach maps of the upper sand unit of the lower Tahara sequence and the upper sand unit of the upper Tahara sequence have revealed that the accumulated thickness of both sand units is a function of available space to fill.
8. From log facies maps, the GR/SP motifs can easily define and respond to the representative lithofacies characterizing the studied units of the Tahara Formation.
9. The Tahara Formation and its lithofacies patterns are recognized that can be ascribed to geographic or stratigraphic architecture factors. These stratigraphic factors related to sea level changes reflected on depositional lithofacies types and sedimentation rates (thickness variations). Other stratigraphic factors are better explained by the characteristics mineralogical composition of the studied sandstone units and the differences in diagenetic processes (compaction, cementation and dissolution). This variation in compositional pathways may reveal some heterogeneity throughout the studied area.
10. Paleostructural factor or structural configuration of the Gullebi Field during and since the time of deposition of Tahara Formation was controlling the pattern of its sandstone and their development at some localities .
11. Major NE-SW striking bounding fault parallel to the axial plane of the Gullebi anticlinal ridge along its NE side, with vertical offset of as much as (50 feet) is present through the Tahara reservoir sandstone as it has been shown to be at least locally sealing.
12. The main through going major NE-SW fault in the southeastern portion of the Gullebi Field could provide for increased fractures in sandstone levels and conduits for fluid flow for more precipitation in these sandstones.

As a result, combination of both stratigraphic and structural factors are influencing the development of sandstone reservoirs of Tahara Formation. The factors responsible for reservoir development and creation of heterogeneity at the Gullebi Field are representative of those encountered within the entire Tahara Formation. Many other reservoirs, especially those in the northern part of the Ghadames Basin, are very similar to those in the Gullebi

Field and owe their development to the same processes. Other reservoirs in the basin owe their origin and complexity to varying combination of the factors outlined here. In each of these reservoirs, the relative influence of depositional, diagenetic and structural processes must be carefully examined in planning future exploration strategies.

Recommendations

The following recommendations are suggested based on the results of this research:

- Better understanding of lithofacies distribution and quality will allow for more accurate reservoir model and that will enable a more realistic recovery and production.
- In spite of the lithofacies variability of the Tahara Formation, sand bodies shape and orientation must be mapped.
- Faulting is present at the SE of the Gullebi Field may control partially the distribution of Tahara sandstones at some levels.
- New exploration concepts related to Tahara sandstone reservoirs in the Gullebi Field can focus on structural framework in addition to traditional stratigraphic techniques.
- Integrating high-resolution stratigraphic correlations with seismic attributes extracted from available 3D data after reprocessing is necessary to image depositional trends of beach-deltaic sandstones and fluvial channels and predict infill locations that will encounter these reservoirs.

References

Abugares, I. Y. (2003). The Petroleum Geology of the Palaeozoic Clastics of the Murzuq Basin, Al'Atshan Saddle and the Southern Part of the Ghadamis Basin, Libya. In The Geology of Northwest Libya (2000), volume II, eds. M. J. Salem, and Khaled. M. Oun, p. 327-350.

Ali, M. T. (1977). Sedimentological Study of the Tahara Formation, Guellebi Area-NC7. NOC, Technical Data Library (TDL) . "ACOCO, Benghazi".

Arabian Gulf Oil Company, (2011) . Lithostratigraphic Chart of Ghadames (Hamada) Basin, NW Libya. Exploration Department, Technical Data Library (TDL) . "AGOCO, Benghazi".

Arduini, M., Barassi M., Golfetto F., Ortenzi A., Serafini G., Tebaldi E.,Trincianti E. and Visentin C., (2003). Silurian-Devonian Sedimentary Geology of the Libyan Ghadamis Basin: Example of an Integrated Approach to the Acacus formation Study. Second Symposium on the Sedimentary Basins of Libya (2000). The Geology of Northwest Libya, vol. 2, p. 183-210.

Banerjee, S., (1980) . Stratigraphic lexicon of Libya. Department of Geo logical Researches and Mining, Bulletin No. 13, Industrial Research Centre, Tripoli , Libya, 300 P.

Beicip, (1972). Western Libya Exploration Study, Final Report, N.O.C., Libya , 197 P.

Beicip, (1973). Western Libya Exploration Study, Oil Potential Zones No. 1 and No. 2 Upper Devonian To Lower Carboniferous prospects. N.O.C., Libya , 8 P.

Beicip, (2011) . Geological & Reservoir Engineering study of the Undeveloped Oil & Gas Fields of Hamada NC7A and Undeveloped Gas reservoirs of Hamada NC5A and NC8A, Reservoir Department, AGOCO, Benghazi.

Belhaj, F., (1996). Palaeozoic and Mesozoic stratigraphy of eastern Ghadamis and western Sirt Basins. First Symposium on the Sedimentary Basins of Libya, Geology of the Sirt Basin, vol. 1. (eds. M.J. Salem, A.J. Mouzughi and O.S. Hammuda), Elsevier, Amsterdam, p. 57-96.

Belhaj, F., (2000). Carboniferous and Devonian stratigraphy- the M'rar and Tadrart reservoirs, Ghadames Basin, Libya. Symposium on Geological Exploration in Murzuq Basin (Eds. M.A. Sola and D. Worsley), Elsevier, Amsterdam, p. 117-142.

Bellini, E. and Massa, D., (1980). A stratigraphic contribution to the Palaeozoic of the southern basins of Libya. Second Symposium on the Geology of Libya. vol. 1 (eds. M.J. Salem and M.T. Busrewil), Academic Press, London, p. 3-56.

Bertello, F., Visentin C. and Ziza W., (2003). An Overview Of The Evolution And The Petroleum Systems Of The Eastern Ghadames (Hamra) Basin – Libya. AAPG Hedberg Conference "Paleozoic and Triassic Petroleum Systems in North Africa", February 18, 2003, Algiers, Algeria.

BjΦrlykke, K., Jahren, J., Mondol, N. H., Marcussen, O., Croize, D., Peltonen, C. and Thyberg, B., (2009). Sediment Compaction and Rock Properties. Department of Geosciences, University of Oslo, Norway. AAPG International Conference and Exhibition presentation, Cape Town, South Africa, 2008.

Boggs, Sam., (1995). Principles of sedimentology and stratigraphy, 2nd edition, Prentice Hall, 774 p.

Boote, D.R.D., Clark-Lowes, D.D., Traut, M.W., (1998). Palaeozoic Petroleum Systems of North Africa. In: Petroleum. Geology of North Africa, (ed. D.S. Macgregor, R.T.J. Moody, D.D. Clark-Lowes), Geol. Soc. Special Publication No. 132, p. 7-68.

Borghi, P. and Chiesa, C., (1940). Cenni geologici e paleontologici sul paleozoico dell'Egghidi Uan Caza nel desserto di Taita (Fazzan occidentale), Bolletino de la Societa Geologica Italiana, v. 2, Tripoli, pp. 123–127.

Bracaccia, V., Carcano, C , and Drera, K., (1991). Sedimentology of the Silurian-Devonian Series in the southeastern part of the Ghadamis Basin. Third Symposium on the Geology of Libya, vol. 5 (eds. M.J. Salem and M.N. Belaid), Elsevier, Amsterdam, p. 1727-1744.

Bulling, T. P. and Breyer, J. A., (1989). Exploring for subtle traps with high-resolution paleogeograph ic maps: Reklaw 1 interval (Eocene) , South Texas. The American Association of Petroleum Geologists Bulletin, vol. No. 1, P.24-39 .

Burki, M. M. and Turner. B., (2003). Hydrocarbon Reservoir Potential of the Tahara Sandstone, Ghadamis Basin, Western Libya. Second Symposium on the Sedimentary Basins of Libya (2000). The Geology of northwest Libya, vol. 2. p. 351-360.

Burki, M. M., (1998). Sedimentological Analysis and Hydrocarbon Potential of the Upper Devonian-Lower Carboniferous Tahara Sandstones, Ghadames Basin; Western Libya. MSc. Thesis, Univ. Durham.

Burollet, P. F., (1960). Libye. Lexique Stratigraphique International, Afrique (dir. R. Furon) Fascicule IVa. Congres Geologique International, Cent. Nat. Rech. Sci. Paris, p. 62.

Burollet, P. F., et al. (1963b). A discussion of Libyan Stratigraphy. Rev. Inst. Petrole. Paris. First Saharan Symposium, Tripoli. Vol. 18, pp. 1323-1325.

Burollet, P.F., (1963a). Reconnaissance geologique dans le sud-est du bassin de Kufra: Petroleum Explo. Soc. Libya Saharan Symposium, First, Tripoli 1963, Inst. Francais petrole Rev., v. 18, pt. 2, p. 1537-1545.

Burollet, P.F., and Byramjee, R., (1969). Sedimentological remarks on Lower Palaeozoic sandstones of south Libya. In: Geology, archaeology and prehistory of the southwestern Fezzan, Libya (ed. Kanes, W.H.). Petroleum Exploration Society of Libya, Eleventh Annual Field Conference, 1969 Tripoli. p. 91-102.

Burt, T.P., Chorley R.J., Brunsden D., Cox N.J., Goudie A.S., (2008). The history of the study of landforms, or the development of Geomorphology. Quaternary and Recent Processes and Forms (1890-1965) and the Mid-Century Revolutions. Geological Society, Miscellaneous Special Publications, vol. 4., London, 1027 p.

Cai, Z. and Owonifaari, F., (2010) Filling Rate of Hydrocarbon Traps Concession NC7A Ghadames Basin, NW Libya, unpublished AGOCO report, Exploration department, Benghazi, p. 1-26.

Campion, K., (2011). Strategies for Well Log Correlation within a Sequence Stratigraphic Framework: Is the Gain Worth the Pain?. Recovery, CSPG CSEG CWLS Convention, p. 1-5.

Canaple, J., (1959). Etude des series continentales Post-Carboniferes du Tinrhert Algero-Libyen. Compagnie des Petroles Total (Libye) Unpublished Report.

Cant, D. J., (1984). Subsurface facies analysis. In: Walker R. G (ed) Facies models. Geological Association of Canada, 297-310.

Chapman, R. E., (1983). Petroleum Geology, Concepts of Sedimentary Basins, (Elsevier, Amsterdam). p. 1-22,.

Collomb, G. R., Manderscheid, G., Jacque, M. and Heller, C., (1959). Etude geologique de la bordure orientale du bassin de Mourzouk. C.P.T.(L) Unpublished Report.

Collomb, G.R., (1962). Etude geologique du Jebel Fezzan et de sa bordure Palaeozoique. Com. Fran, du Pet, Notes et Mem. no. 1, p. 7-35.

Compagnies Pétrolieres, (1964). Essai de nomenclature lithostratigraphique du Cambro-Orovicien Saharien, Soc. Géol. Fr. Mem. hors ser., 2, p. 54.

Conant, L. C. AND Goudarzi, G. H., (1964). Geological Map of Kingdom of Libya. U.S. Geol.

Cotillon, P., (1992) Stratigraphy, Département des Sciences de la Terre Université Claude-Bernard Lyon I, France. Translated by James P.A. Noble Department of Geology University of New Brunswick, Canada.

Cridland, R., (1991). Seismic Stratigraphic Evaluation of NC2, AGOCO unpublished AGOCO report., Technical Data Library (TDL) . "ACOCO, Benghazi”.

Crowder, R. K., (1990). Permian and Triassic Sedimentation in the Northern Brooks Range, Alaska: Deposition of the Sadlerochit Group: AAPG Bull., vol. 74, no. 9, p. 1351-1370.

De lapparent, A.F. and Lelubre, M., (1948). Interpretation stratigraphique des series continentals entre Ohanet et Bourarhet (Sahara central). C.R. Acad. Sci. Paris, vol. 227, p. 1106-1108.

Desio, A., (1936a). Riassunto sulla costituzione geologica, del Fezzam. Boll. Soc. Geol. Ital., 3 fig., I carta geol. scala 1:3,000,000, Roma. Vol. 55, No. 2, pp. 319-356.

Desio, A., (1936b). Prime notizie sulla presenza del Silurico fossilifero nel Fezzan. Boll. Soc. Geol. Ital. vol. 55, p.116-120, Roma.

Echikh, K. and Suleiman S., (1982). Preliminary Geological Study and Petroleum Evaluation of Ghadames Basin. Exploration department, NOC, Tripoli.

Echikh, K., (1998). Geology and hydrocarbon occurrences in the Ghadames Basin, Algeria, Tunisia, Libya. In: Petroleum Geology of North Africa, (ed. D.S. Macgregor, R.T.J. Moody, D.D. Clark-Lowes), Geol. Soc. Special Publication No. 132, p. 109-130.

Elfigih, O. B., (1991). The Sedimentology and Reservoir Characteristics of the Lower Acacus Formation, NC2 Concession, Hamada Basin, NW Libya. Msc thesis, Department of Earth Sciences, Memorial University of Newfoundland, Canada.

Elfigih, O. B., (2000). Regional diagenesis and its Relation to Facies Changes in the Upper Silurian, Lower Acacus Formation, Hamada (Ghadames) Basin, Northwestern Libya. PhD thesis, Department of Earth Sciences, Memorial University of Newfoundland, Canada.

El-Hawat, A.S. and Bezan, A.M., (1998). Early Palaeozoic event stratigraphy of western Libya: glacio-eustatic and tectonic signatures and their impact on hydrocarbon exploration (abstract only). Symposium on Geological Exploration in Murzuq Basin, Sabha, 20-22nd September 1998. Book of abstracts.

El-Mehdawi, A.D., (2000). Palynology of the upper Tahara Formation in concession NC 7A, Ghadames Basin. Symposium on Geological Exploration in Murzuq Basin (eds. M.A. Sola and D. Worsley), Elsevier, Amsterdam, p. 273-294.

Elruemi, W., (2003), Geologic Evolution of Ghadamis Basin-Impact on Hydrocarbon Prospectivity. In The Geology of Northwest Libya (2000), vol. 2, eds. M. J. Salem, and Khaled. M. Oun, p. 327-350.

El-Rweimi, W.S., (1991). Geology of the Aouinet Ouenine and Tahara Formations, Al Hamada al Hamra area, Ghadamis Basin. Third Symposium on the Geology of Libya, vol. 6 (eds. M.J. Salem, A.M. Sbeta and M.R. Bakbak), Elsevier, Amsterdam, p. 2185-2194.

Elwarfali, H. O., (1990). Sedimentological Analyses of the Tahara Formation in HH1-NC7A (Al Hamada Basin) AGOCO. unpublished AGOCO report., Technical Data Library (TDL) . "ACOCO, Benghazi".

Evenick, J. C., (2008). Introduction to well logs and subsurface maps: Tulsa, PennWell, 236p.

Folk, R. L., (1980) . Petrography of sedimentary rocks . Hemphill Publishing Company , Austin, Texas, 184P.

Furst, M. and Klitzsch, E. (1963). Late Caledonian paleogeography of the Murzuk basin. Rev. Inst. Fr. Petrole, 4 fig., Eng. sum., Paris. Vol. 18, No. 10, pp. 1472-1484.

Galloway, W. E. and Hobday, D. K., (1983). Terrigenous clastic depositional systems. Springer Vertag, New York. 423p.

Ghori, K.A. R., and Mohammed. R.A., (2003). Petroleum System Modelling in Ghadames Basin of NW Libya. Second Symposium on the Sedimentary Basins of Libya (2000). The Geology of northwest Libya, vol. 2. p. 245-259.

Goudarzi, G.H., (1970). Geology and mineral resources of Libya: a reconnaissance. U.S. Geol. Surv. Prof Paper no. 660, Washington, 104p.

Greensmith, J. T., (1988). Petrology of the Sedimentary Rocks, London, Boston, Sydney, Wellington: Unwin Hyman, 7th ed. ix + 262 pp.

Gundobin, V.M., (1985). Sheet Qararat al Marar (NH 33-13), Geological Map of Libya, scale 1:250,000, Explanatory Booklet, Industrial Research Centre, Tripoli.

Hallett, D., (2002). Petroleum Geology of Libya. 1st edition Elsevier Science B.V. Amsterdam , the Netherlands, 235pp.

Harwood, G., (1988). Microscopic Techniques : II , Principles of Sedimentary Petrology (Chapter 5). I n : Techniques i n sedimentology (ed. Tucker, M. , 1988) , P.108-173.

Hassi, I. A. A., (1993). Dynamic Stratigraphy of the Tahara Formation, Hamada Basin, western Libya. Msc thesis, Department of Geology and Applied Geology, University of Glasgow, Scotland.

Havlicek, V. and Massa D., (1973): Brachiopodes de l'Ordovicien superieur de Libye Occidentale: implications stratigraphiques regionales. Geobios, 1 fig., 4 pl., Eng. Sum., Lyon. Vol. 6, No. 4, pp. 267-290,.

Hoen, E. W., (1968). Geology of the Murzuk Basin, Unpubl. Rep. Amoseas Ltd., December 4, 1968, Tripoli, 85 p.

Jacque, M., (1962). Reconnaissance geologique du Fezzan oriental. Notes et Mem, Comp. Fran. Pet. No. 5, 44p.

Kilian, C., (1931). Des principaux complexes continentaux du Sahara. C.R. Soc. Geol. Fr. No. 9, p. 109-111.

Klitzsch, E., (1963). Geology of the north-east flank of the Murzuk Basin (Djebel ben Ghnema-Dor el Gussa area). First Saharan Symposium. Rev. Inst. Fran. Pet. special volume, p. 97-113.

Klitzsch, E., (1965). Ein profil aus dem typusgebiet gotlandischer und devonische schichten der zentralsahara (westrand Murzukbecken, Libyen). Erdol u. Kohle. Deut. vol. 18, p. 605-607.

Klitzsch, E., (1966). Comments on the Geology of the Central Parts of Southern Libya and Northern Chad. Petrol. Explor. Soc. Libya, 8th Ann. Field Conf., 1966, South-Central Libya, 12fig, correl. Chart, Tripoli, pp.1-17.

Klitzsch, E., (1969). Stratigraphic section from the type areas of Silurian and Devonian strata at western Murzuk Basin (Libya). In: Geology, archaeology and prehistory of the southwestern Fezzan, Libya (ed. Kanes, W.H.). Petroleum Exploration Society of Libya, Eleventh Annual Field Conference, p. 83-90.

Klitzsch, E., (1971). The structural development of parts of north Africa since Cambrian time. First Symposium on the Geology of Libya (ed. C. Gray). Faculty of Science, University of Libya, Tripoli, p. 253-262.

Klitzsch, E., Lejal-Nicol, A. and Massa, D. (1973). Le Siluro-Devonien a Psilophytes et Lycophytes du bassin de Mourzouk, Libye. C.R, Acad. ScL Paris, vol. 277, ser. D, p. 2465-2467.

Koutsoukos, E. A. M., (2005). Stratigraphy: Evolution of a Concept. In: E. A. M. Koutsoukos (ed.), Applied Stratigraphy, 3-19, Springer.

Krumbein, W. C., and Sloss, L. L., (1959). "Stratigraphy and Sedimentation." Freeman, San Francisco. 497pp.

Lelubre, M., (1946). Le Tibesti septentrionale. Esquisse morphologique et stmcturale. C.R. Acad. Sci. Colon. vol. 6. p. 337-357.

Lelubre, M., (1948). Le Paleozoique du Fezzan sud-oriental. CR. Soc Geol. Fr., Vol. 18, No.4, pp. 79-81, Paris.

Lelubre, M., (1952). Apercu sur la geologie du Fezzan. Bull. Serv. Carte Geol. d’ Algerie, Travaux Recents Collaborateurs, 4 fig., biblio., Alger, No. 3, pp. 109-148.

Lüning, S., Craig J., Loydell D.K., Storch P., Fitches B., (2000). Lower Silurian ‘hot shales’ in North Africa and Arabia: regional distribution and depositional model. Earth-Science Reviews. Elsevier Science B.V. pp. 121–200

Mamgain, V.D., (1980). The pre-Mesozoic (Precambrian to Palaeozoic) stratigraphy of Libya - a reappraisal. Bulletin No. 14. Industrial Research Centre, Tripoli, 104p.

Maria, F. S. D. S., (1991). Ghadames Basin Regional Study Analysis and Evaluation, AGOCO intrernal report, Technical Data Library (TDL) . "ACOCO, Benghazi”. unpublished AGOCO report.

Massa, D. and Collomb, G.R., (1960). Observations nouvelles sur la region d'Aouinet Ouenine et du Djebel Fezzan (Libye). Proc. 21st Int. Geol. Cong. Copenhagen, pt. 12, p. 65-73.

Massa, D. and Moreau-Benoit, A., (1976). Essai de synthese stratigraphique et palynologique du System devonien en Libye occidentale. Rev. Inst. Fr. Petr. vol. 31, p. 287-333. 5 fig., 8 pl., Paris.

Massa, D., Termier, G. and Termier, H., (1974). Le Carbonifere de Libye occidentale. Comp. Fr. de Petrole, Notes et Mem., 5 + 11 fig., 2 tabl., 7 text-pl.h.t, Paris, No.11, pp. 139-206.

Miall, A. D., (2000). Principles of sedimentary Basin Analysis, 3rd edition. Springer Verlag, Berlin, 616pp.

Morton-Thompson, D. and Woods, A. M., (1993). Development Geology Reference Manual. AAPG Methods in Exploration Series, No. 10. pp.541.

Owonifaari, F., (2009). Depth Map of Tahara Formation, Gullebi Field, Concession NC7A. Exploration Department, AGOCO, Benghazi.

Reading, H.G. (ed.) (1986). Sedimentary Environments and Facies, 2nd edition. Oxford: Blackwells.

Reineck, H.-E., and Singh, I.B., (1980). Depositional Sedimentary Environments, 2nd edn. Berlin: Springer- Verlag. 551 p.

Rider, M. H., (1990). Gamma-ray log shape used as a facies indicator: critical analysis of an oversimplified methodology. In: Hurst A., Lovell M. A. and Morton A. C (eds) Geological Applications of Wireline Logs. Geological Society Special Publication, 48, 27-37.

Schmidt, V. & McDonald, D.A., (1979) The role of secondary porosity in the course of sandstone diagenesis. In: Aspects of Diagenesis. (eds Scholle, P.A. & Schluger, P.R.) Society of Economic Paleontologists and Mineralogists Special Publication 29, pp. 175–207.

Selley, R. C., (1976). Subsurface environmental analysis of North Sea sediments. American Association of Petroluem Geologists Bulletin, 60, 184-195 pp.

Selley, R.C., (2000). Applied Sedimentology, 2nd Edition. Academic Press, London.

Serra, O., (1985). Sedimentary Environments from wireline logs (Mark of Schlumberger), 1st . Edition , 211 p .

Serra, O., (1989). Sedimentary Environments from wireline logs (Mark of Schlumberger), 2nd . Edition , 243 p.

Shah, S.H.A., Mansouri, A. and El Ghoul, M., (1993). Palaeozoic sandstone reservoirs of the Hamada Basin, NW Libya: effects of synsedimentary processes on porosity. Journ. Pet. Geol. vol. 16. p. 345-352.

Shelton, J. W., (1971). Correlation sections and log maps in determination of sandstone trends: AAPG Bulletin, v. 56, no. 8, p. 1541–1544.

Shepherd, M., (2009). Oil field production geology: AAPG Memoir 91, section 2. p.96.

Sikander, A.H., (2003). The geology, structure and hydrocarbon potential of the Ghadamis and Murzuq Basins - an overview. Second Symposium on the Sedimentary Basins of Libya (2000). The Geology of northwest Libya, vol. 2, p. 281-326.

Sikander, A.H., Basu, S. and Rasul, S.M., (2003). Geochemical source-maturation and volumetric evaluation of lower Palaeozoic source rocks in the west Libyan basins. Second Symposium on the Sedimentary Basins of Libya (2000). The Geology of northwest Libya, vol. 3. p. 3-53.

Tawadros, E. E., (2011). Geology of North Africa. CRC Press. p. 931.

Teknica, (1995) . Exploitation Evaluation Study, B&F Pools, Concession NC2, Technical Data Library (TDL), Arabian Gulf Oil Company (AGOCO), Benghazi.

Teknica, (1997) . Exploitation Evaluation Study, Gullebi Field, Concession NC7A, Teknica reports, Technical Data Library (TDL), Arabian Gulf Oil Company (AGOCO), Benghazi.

Underdown, R., and Redfern, J., (2007), The Importance of Constraining Regional Exhumation in Basin Modelling: a Hydrocarbon Maturation History of the Ghadames Basin, North Africa., Petroleum Geoscience, V 13, p. 253-270.

Underdown, R.H., (2006). An Integrated Basin Modelling Study of the Ghadames Basin, North Africa. PhD thesis. University of Manchester.

Vos, R.G., (1981b). Sedimentology of an Ordovician fan delta complex, western Libya. Sedimentary Geology, vol. 29, p. 153-170.

Whitbread, T. and Kelling, G., (1982). Mrar Formation of western Libya - evolution of an early Carboniferous delta system. Bull. Amer. Assoc. Pet. Geol. vol. 66, p. 1091-1107.

Worden, R. H. and Morad, S., (2000). Quartz cementation in oil field sandstones: a review of the key controversies. In: Quartz Cementation in Sandstones. Spec. Publs int. Ass. Sediment. 1-20p.

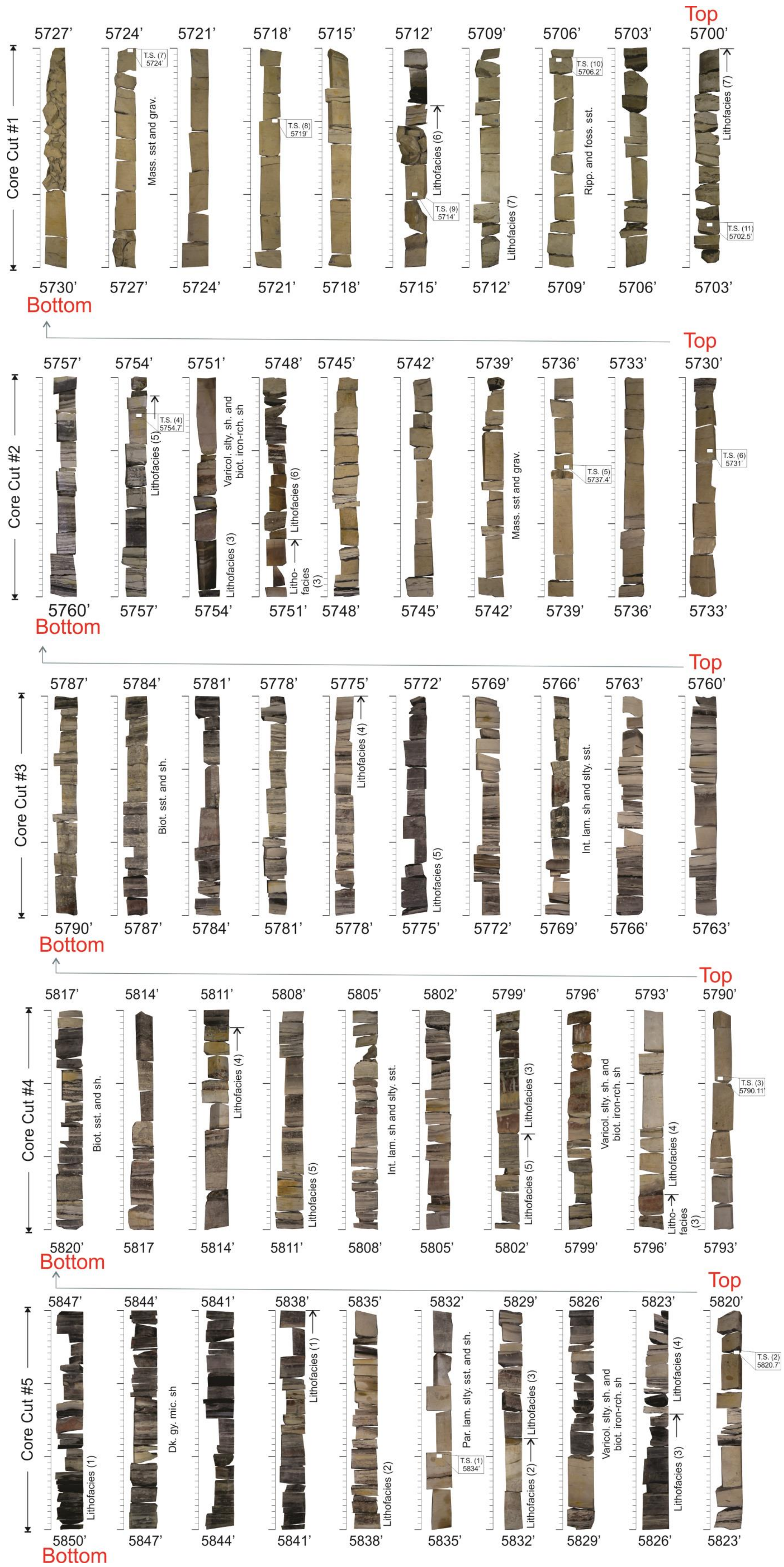
Younis, A.E., (2013). Regional Subsurface Facies Distribution of Upper-Ordovician Memouniat Formation, Ghadames (Hamada) Basin, NW Libya. Msc thesis, Departement of Earth Sciences, Benghazi University, Libya.

Zuffa, G.G., (1985). Optical analyses of arenites: influence of methodology on compositional results: in ZUFFA G.G., ed., Provenance of Arenites, NATO-ASI, Reidel Publ. Co., Dordrecht, p. 165-189.

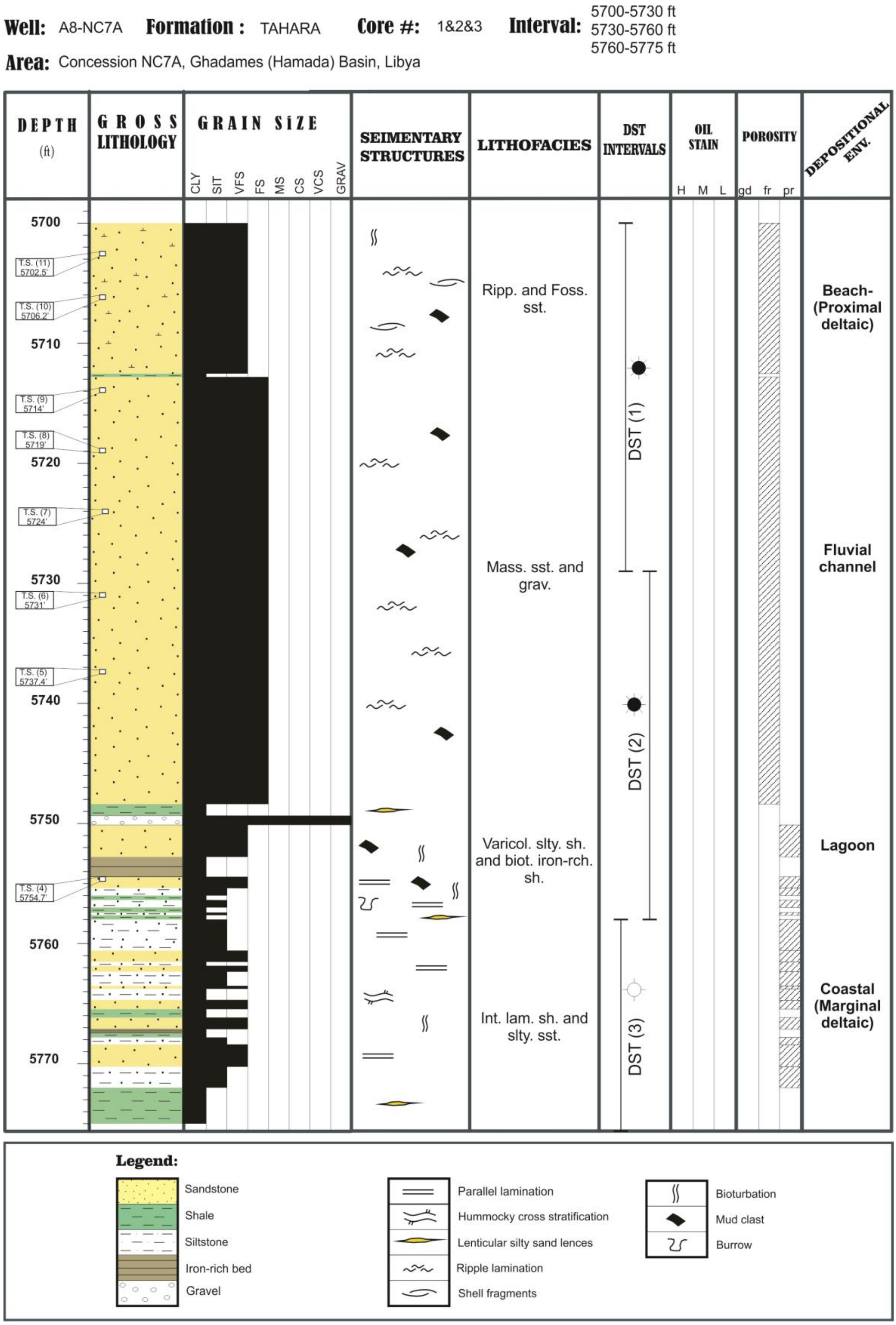
APPENDICES

APPENDIX I

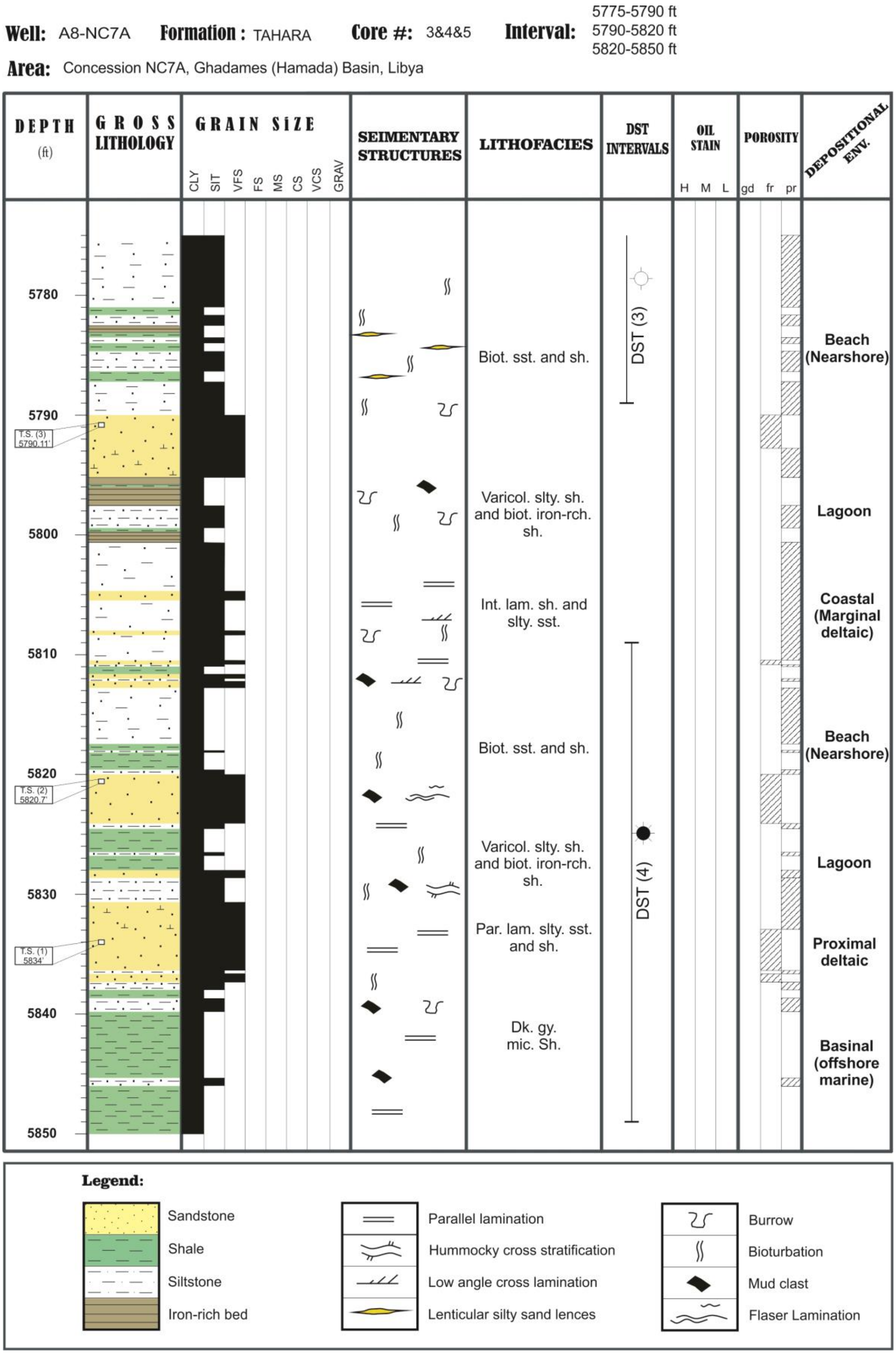
CORE PHOTOGRAPH AND CORE DESCRIPTION OF THE TAHARA FORMATION, CONCESSION NC7A, GHADAMES BASIN



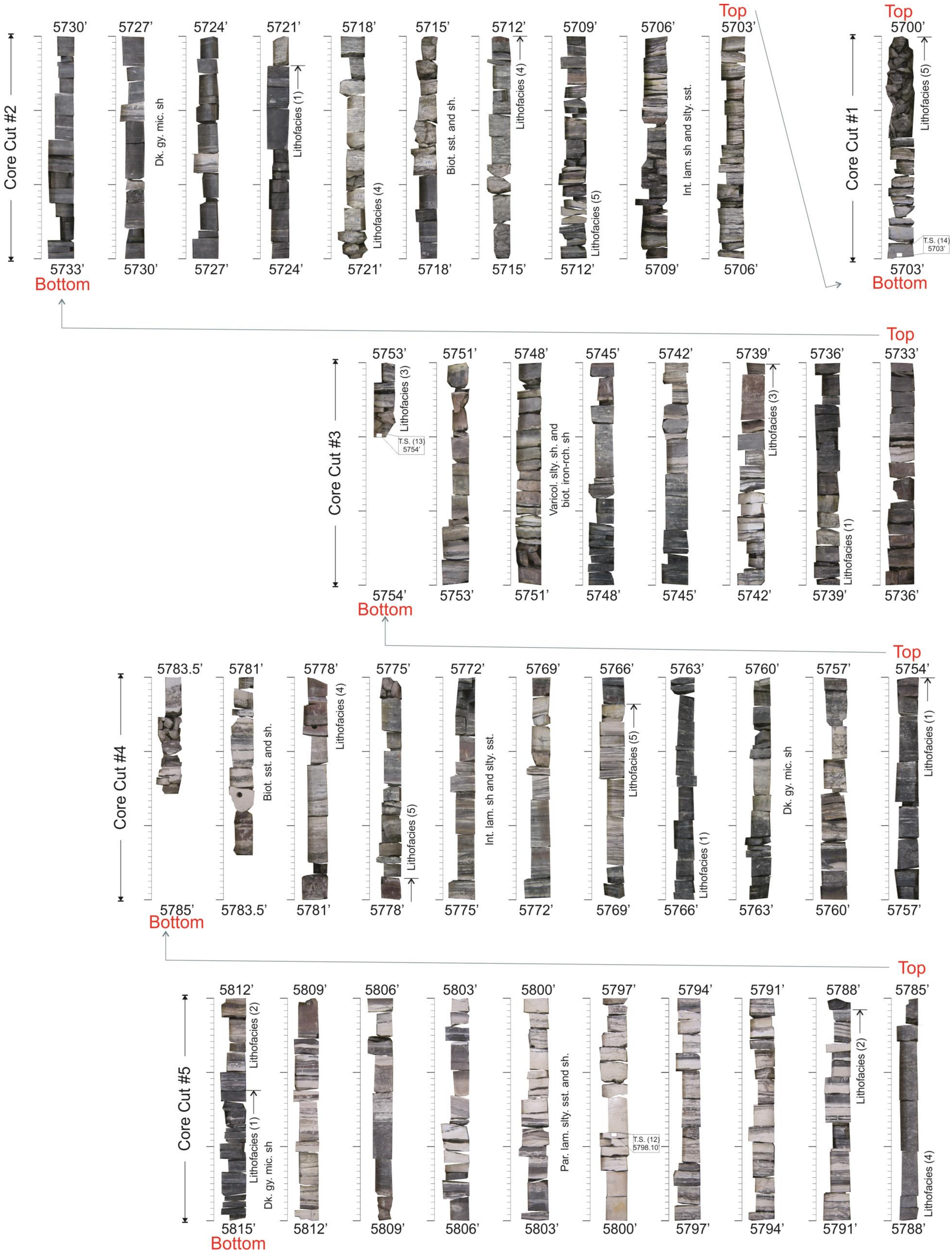
App.I.1. Photograph of cores #1 (5700'-5730'), #2 (5730'-5760'), #3 (5760'-5790'), #4 (5790'-5820'), #5 (5820'-5850'), of Tahara Formation in well A8-NC7A, concession NC7A, Ghadames Basin. (Detailed description of lithofacies are included in App.I.2 and App.I.3).



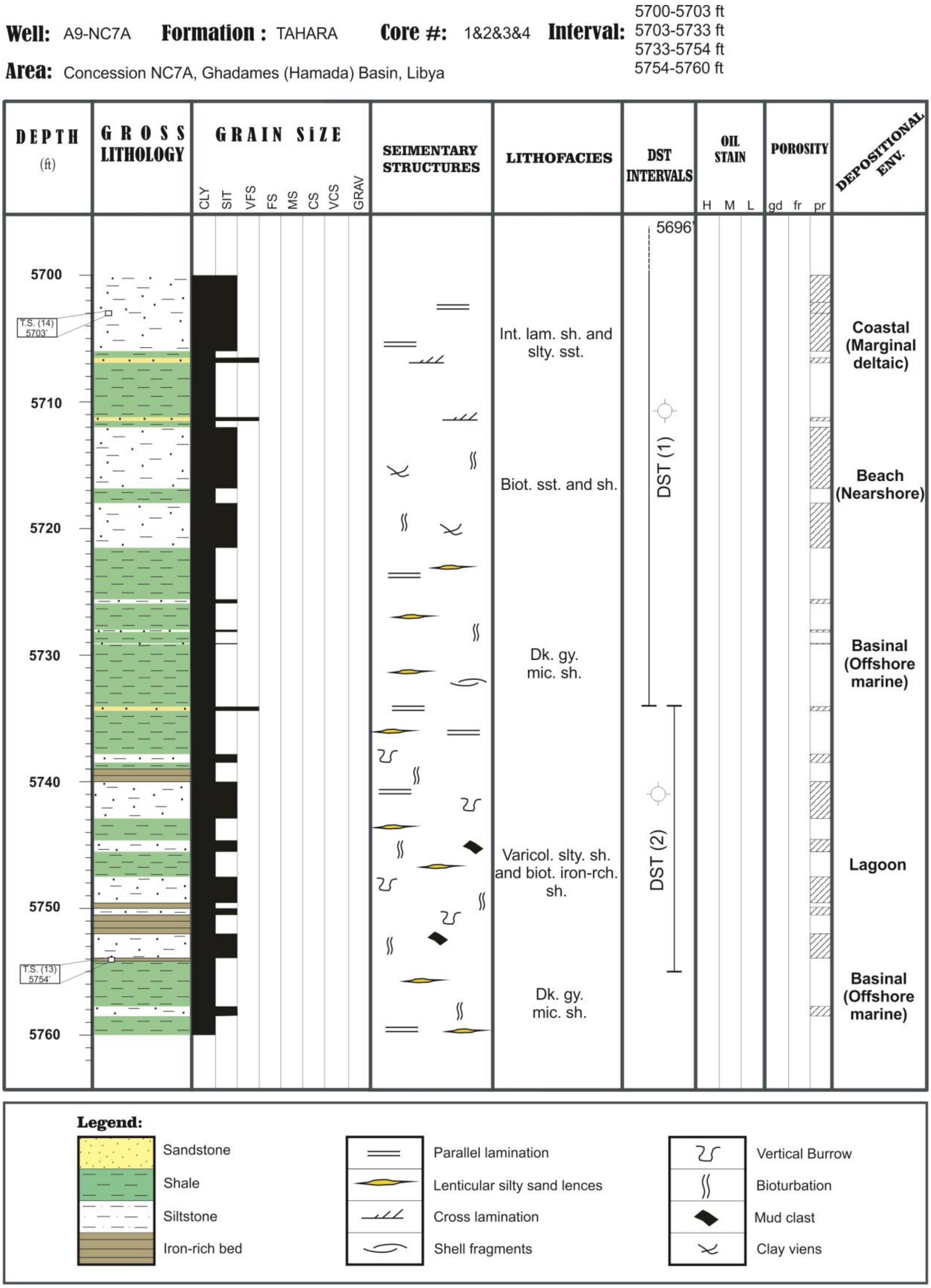
App.I.2. Detailed core description of the cored interval (5700'-5775'), showing lithofacies of Tahara Formation, in well A8-NC7A, concession NC7A, Ghadames Basin.



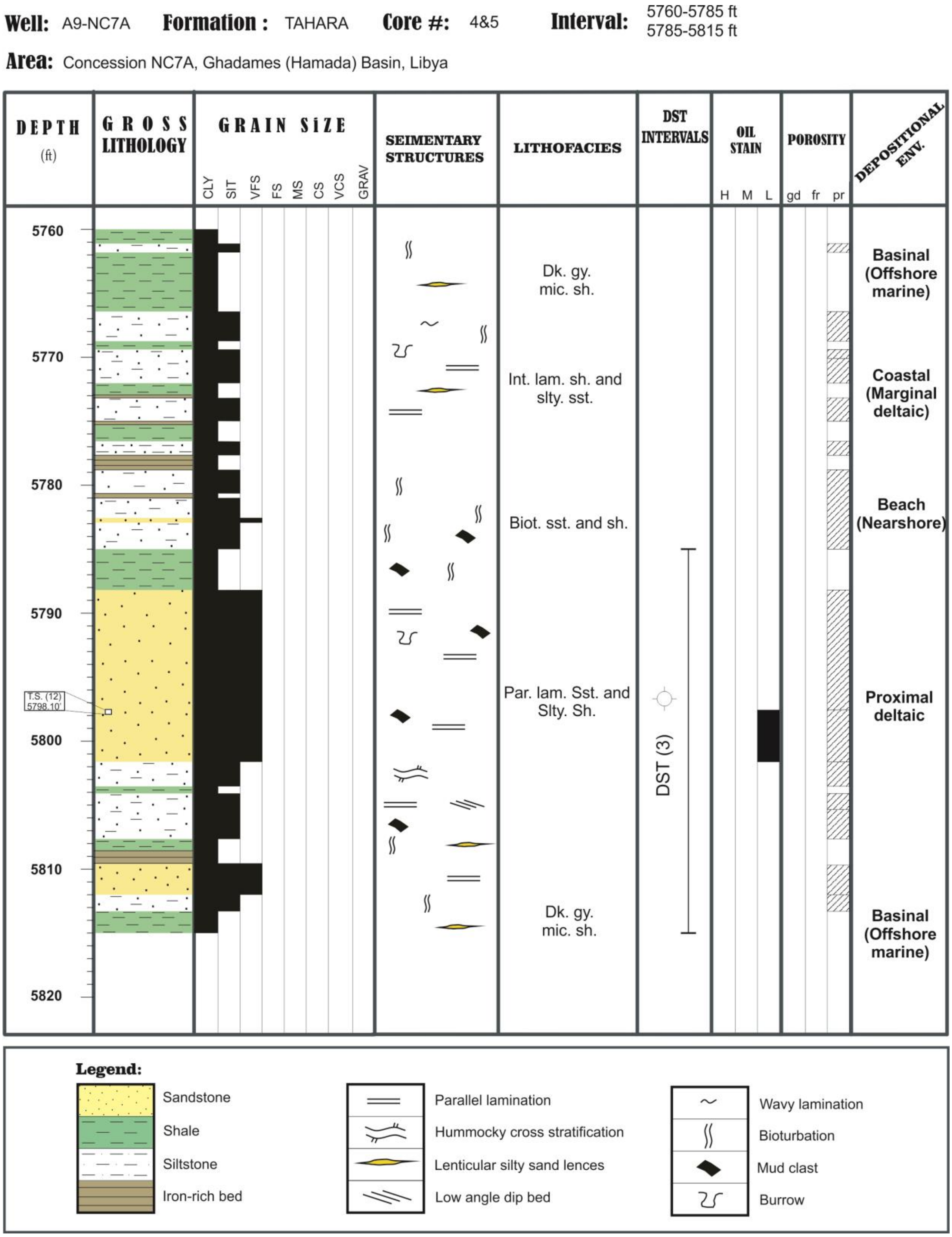
App.I.3. Detailed core description of the cored interval (5775'-5850'), showing lithofacies of Tahara Formation, in well A8-NC7A, concession NC7A, Ghadames Basin.



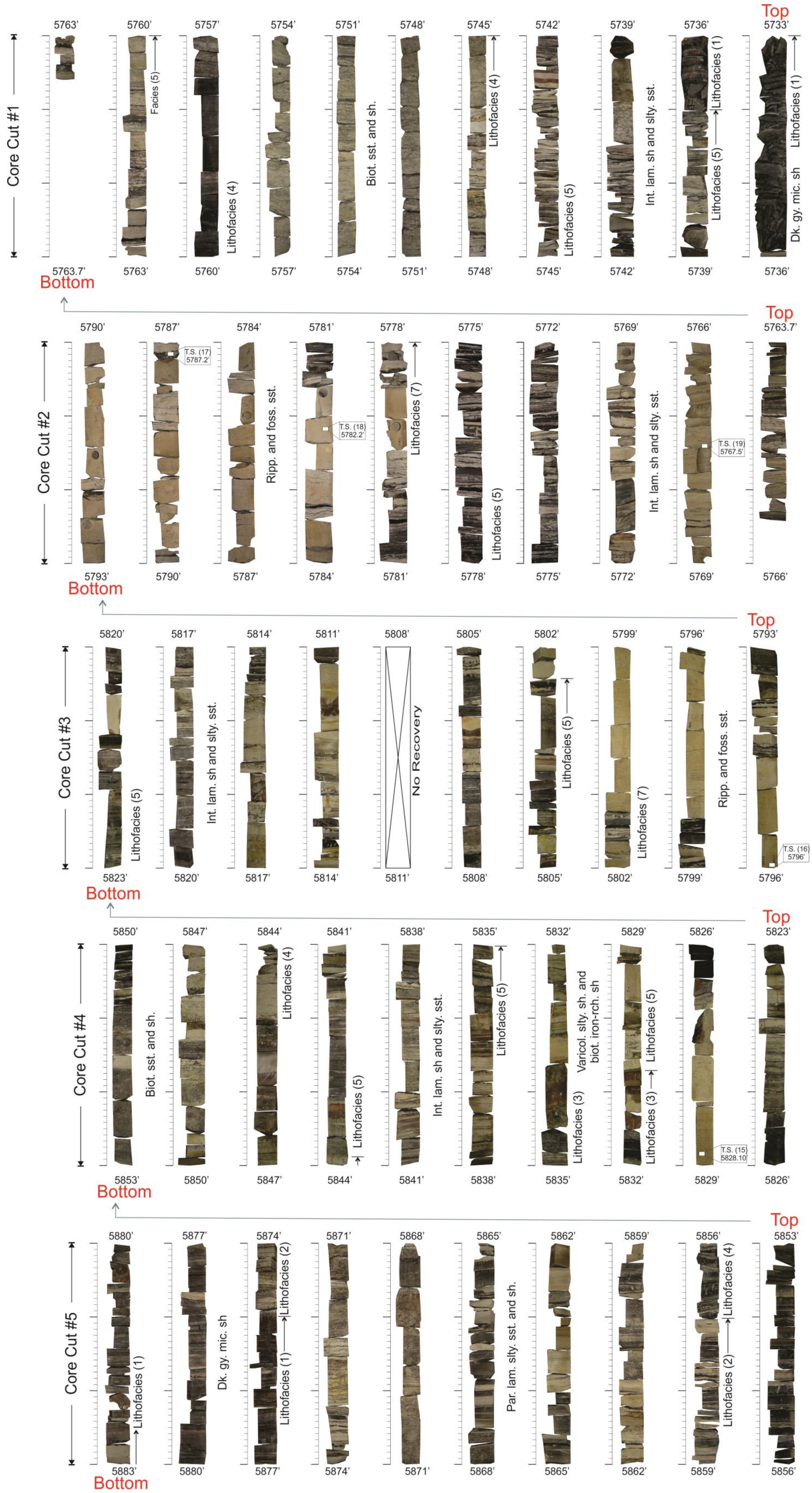
App.I.4. Photograph of cores #1 (5700'-5703'), #2 (5703'-5733'), #3 (5733'-5754'), #4 (5754'-5785'), #5 (5785'-5815'), of Tahara Formation in well A9-NC7A, concession NC7A, Ghadames Basin. (Detailed description of lithofacies are included in App.I.5 and App.I.6).



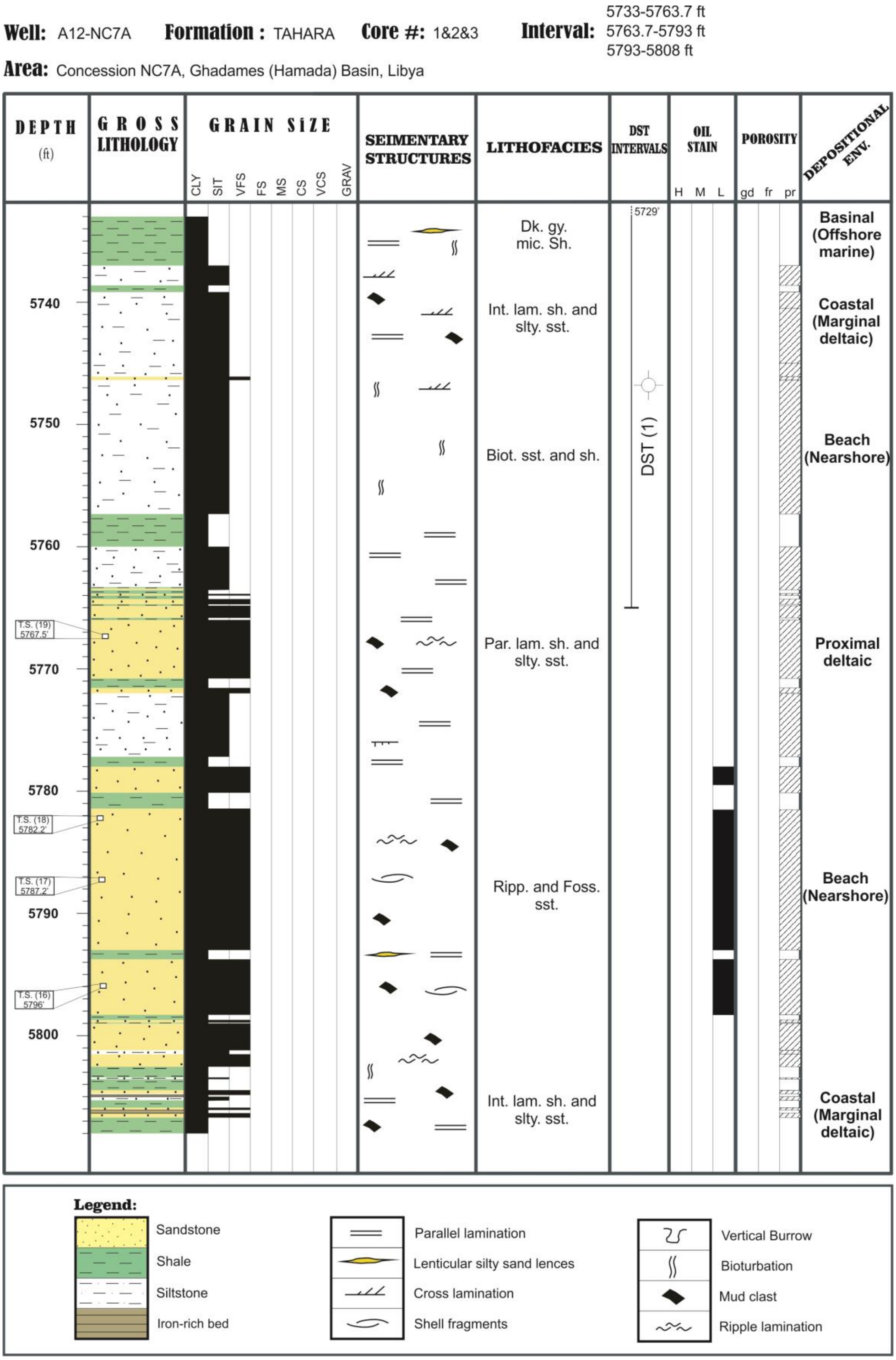
App.I.5. Detailed core description of the cored interval (5700'-5760'), showing lithofacies of Tahara Formation, in well A9-NC7A, concession NC7A, Ghadames Basin.



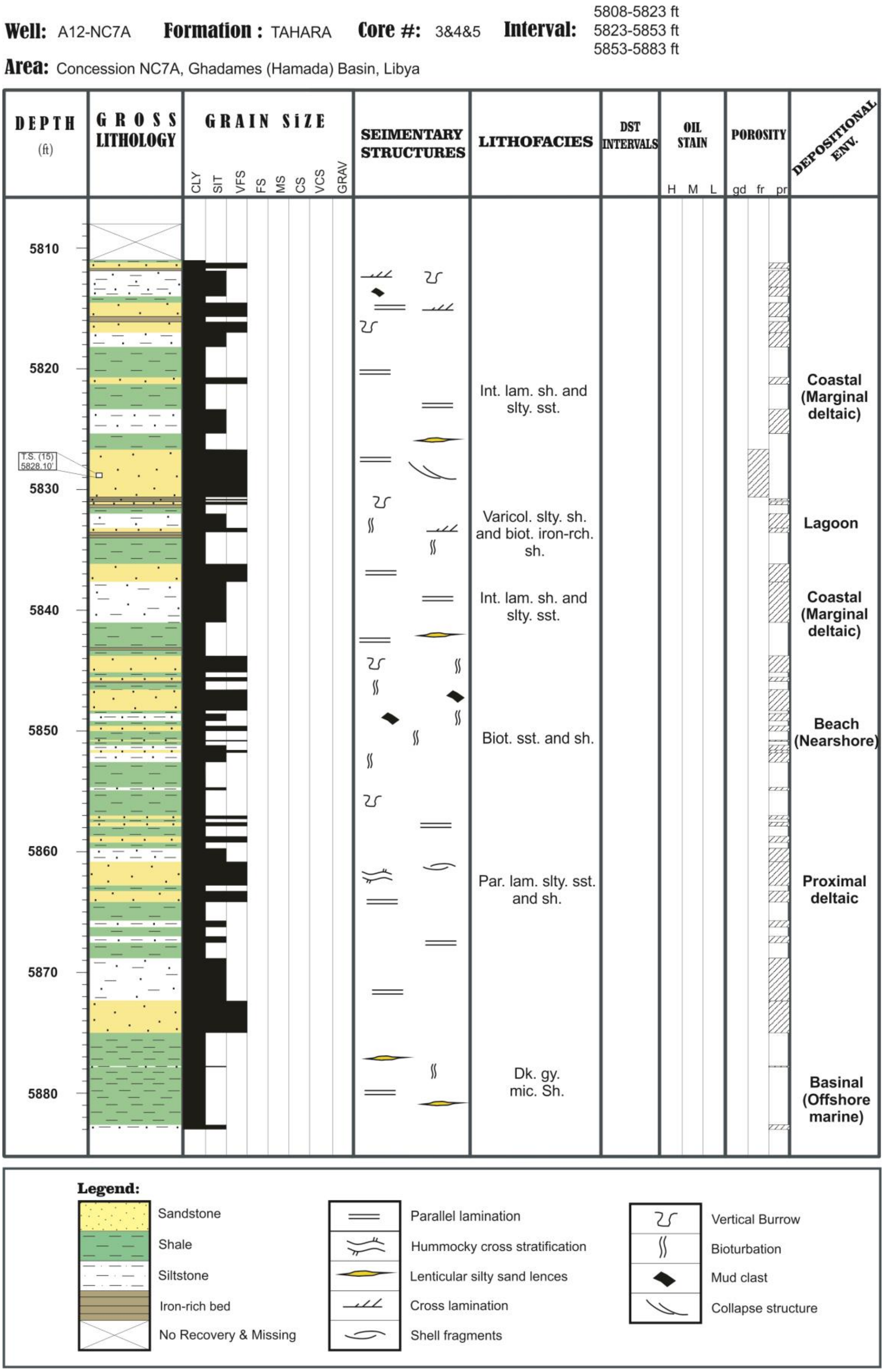
App.I.6. Detailed core description of the cored interval (5760'-5815'), showing lithofacies of Tahara Formation, in well A9-NC7A, concession NC7A, Ghadames Basin.



App.I.7. Photograph of cores#1 (5733'-5763.7'), #2 (5763.7'-5793'), #3 (5793'-5823'), #4 (5823'-5853'), #5 (5853'-5883'), of Tahara Formation in well A12-NC7A, concession NC7A, Ghadames Basin. (Detailed description of lithofacies are included in App.I.8 and App.I.9).

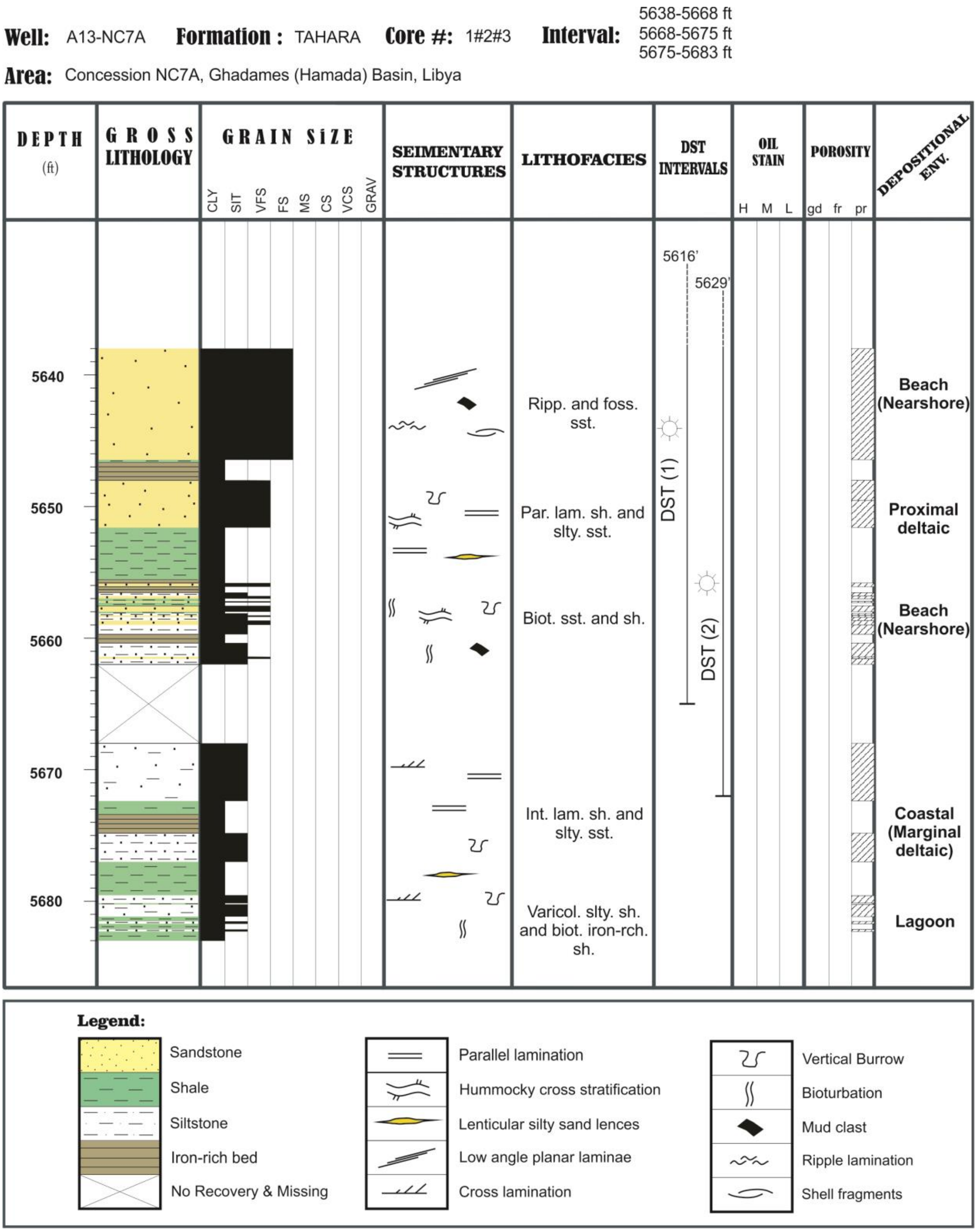


App.I.8. Detailed core description of the cored interval (5733'-5808'), showing lithofacies of Tahara Formation, in well A12-NC7A, concession NC7A, Ghadames Basin.

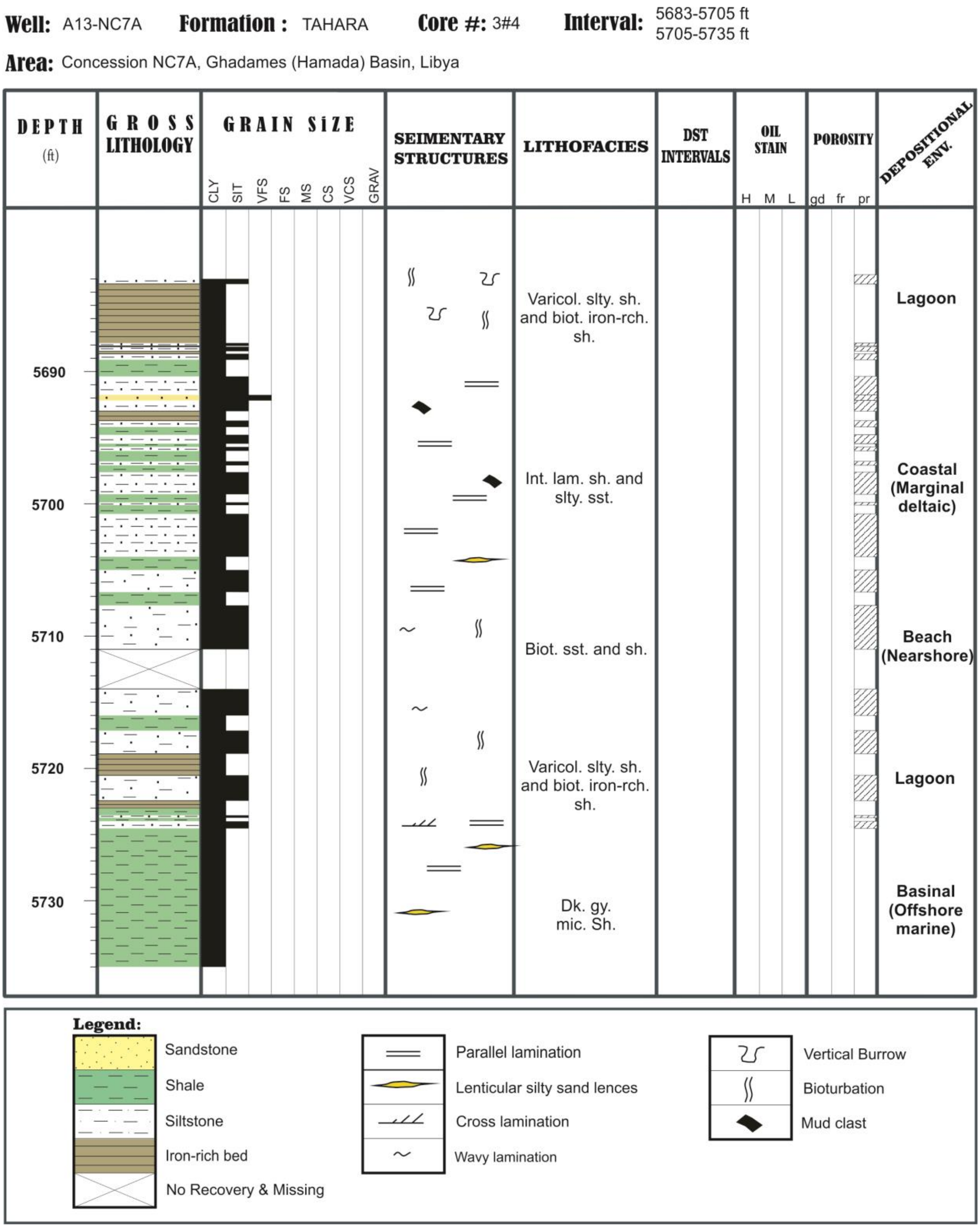


App.I.9. Detailed core description of the cored interval (5808'-5883'), showing lithofacies of Tahara Formation, in well A12-NC7A, concession NC7A, Ghadames Basin.

App.I.10. Photograph of cores #1 (5638'-5662'), #2 (5662'-5675'), #3 (5675'-5705'), #4 (5705'-5735'), of Tahara Formation in well A13-NC7A, concession NC7A, Ghadames Basin. (Detailed description of lithofacies are included in App.I.11 and App.I.12).

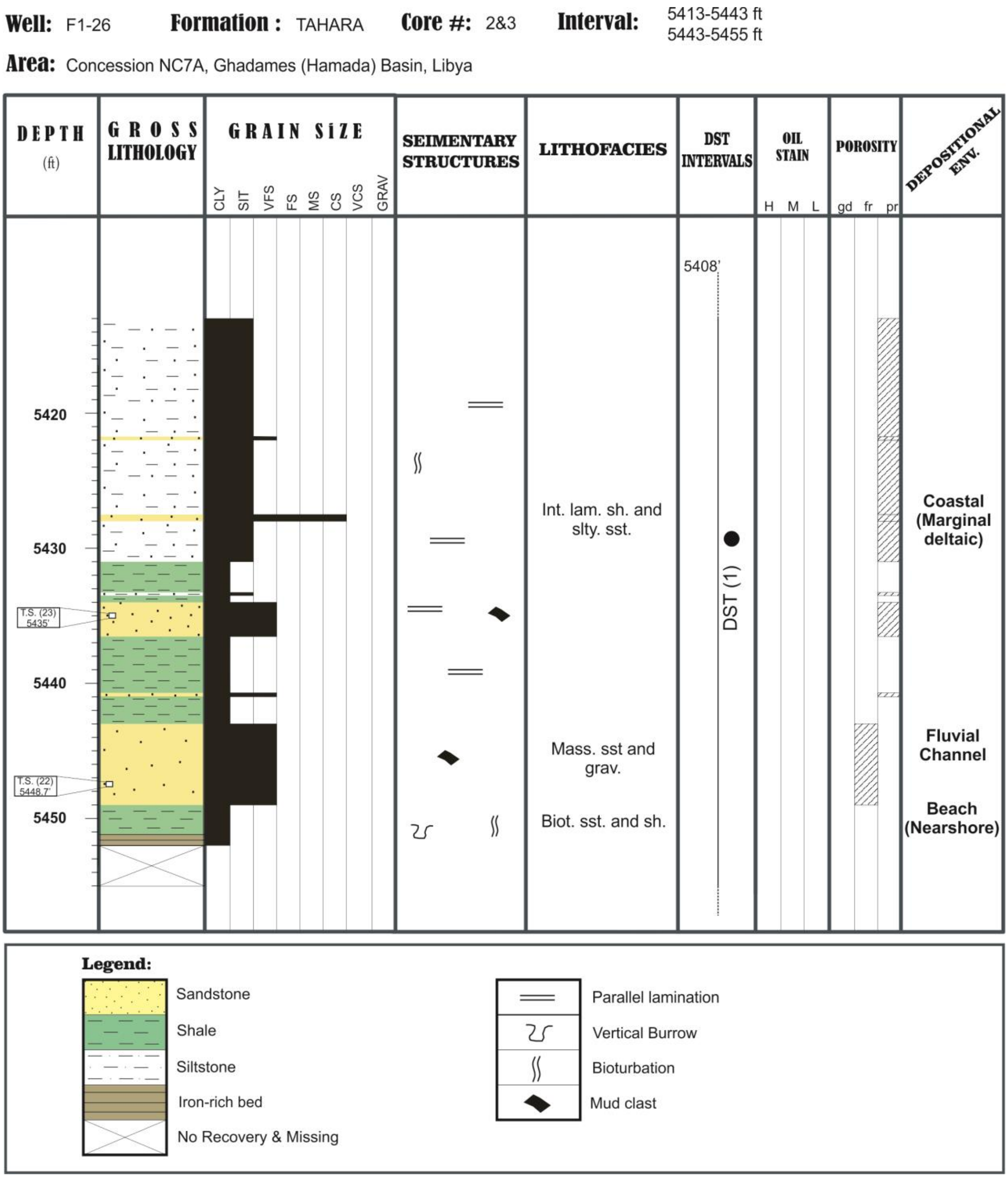


App.I.11. Detailed core description of the cored interval (5638'-5683'), showing lithofacies of Tahara Formation, in well A13-NC7A, concession NC7A, Ghadames Basin.

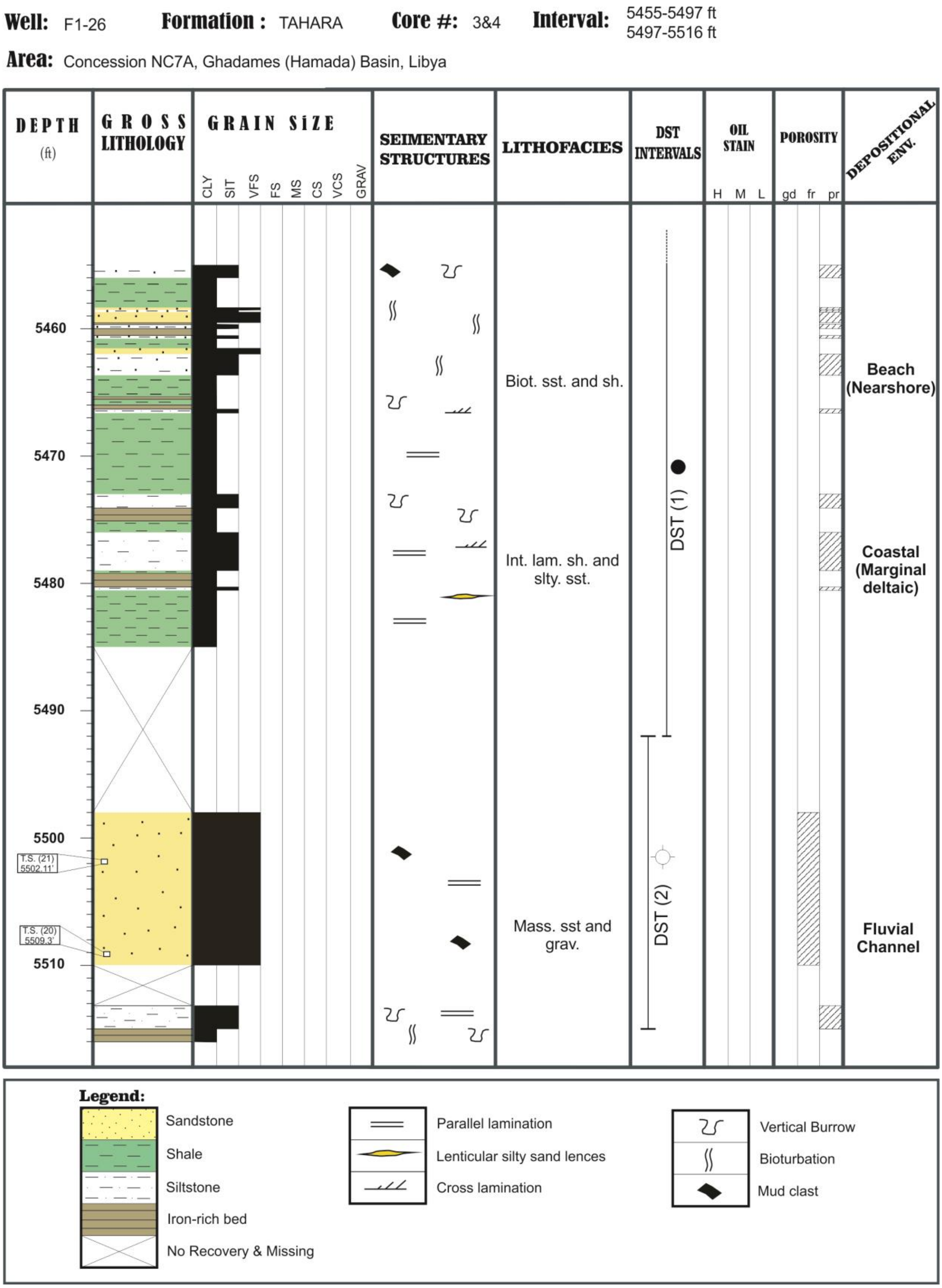


App.I.12. Detailed core description of the cored interval (5683'-5735'), showing lithofacies of Tahara Formation, in well A13-NC7A, concession NC7A, Ghadames Basin.

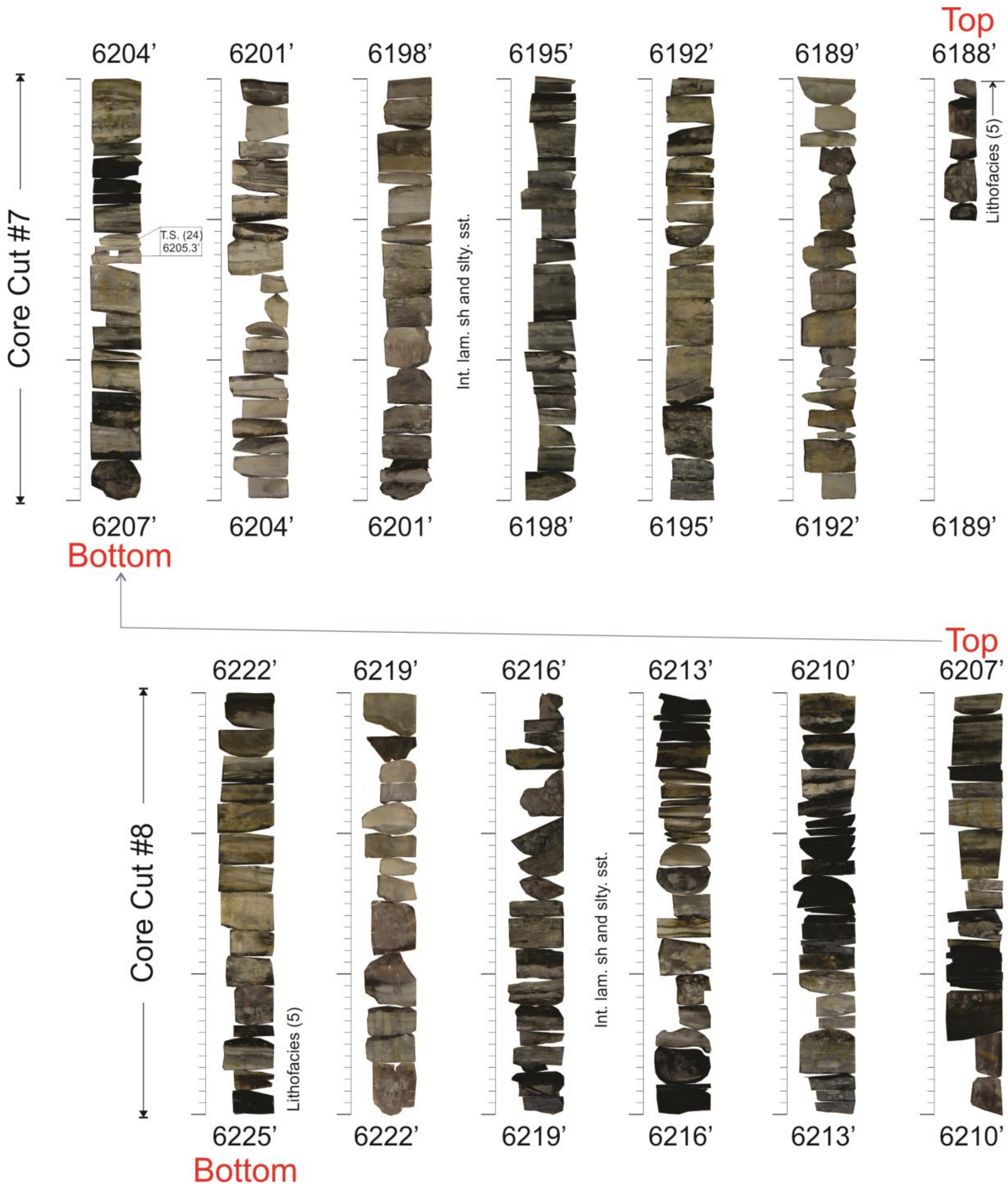
App.I.13. Photograph of cores #2 (5413'-5443'), #3 (5443'-5497'), #4 (5497'-5516'), of Tahara Formation in well F1-26, concession NC7A, Ghadames Basin. (Detailed description of lithofacies are included in App.I.14 and App.I.15).



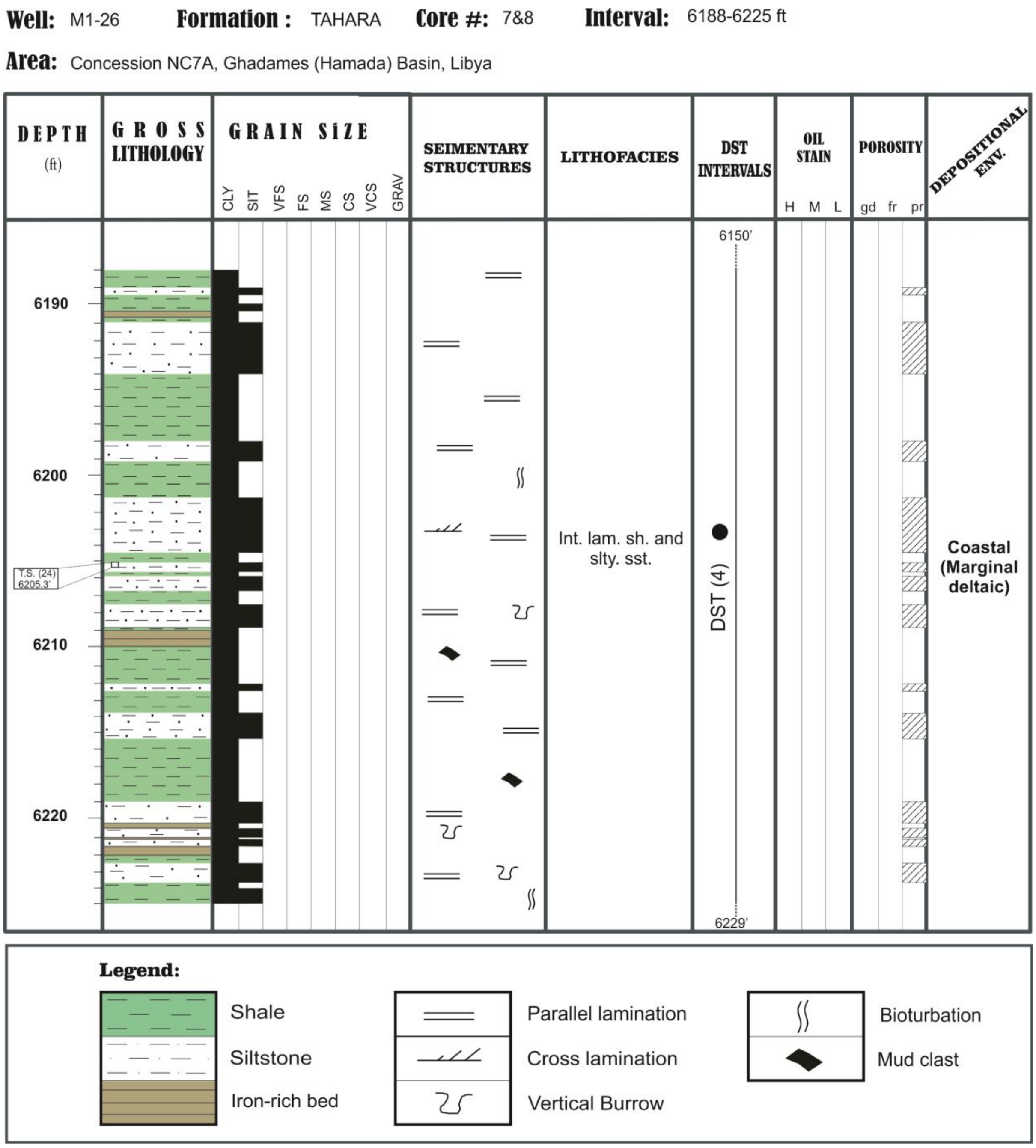
App.I.14. Detailed core description of the cored interval (5413'-5455'), showing lithofacies of Tahara Formation, in well F1-26, concession NC7A, Ghadames Basin.



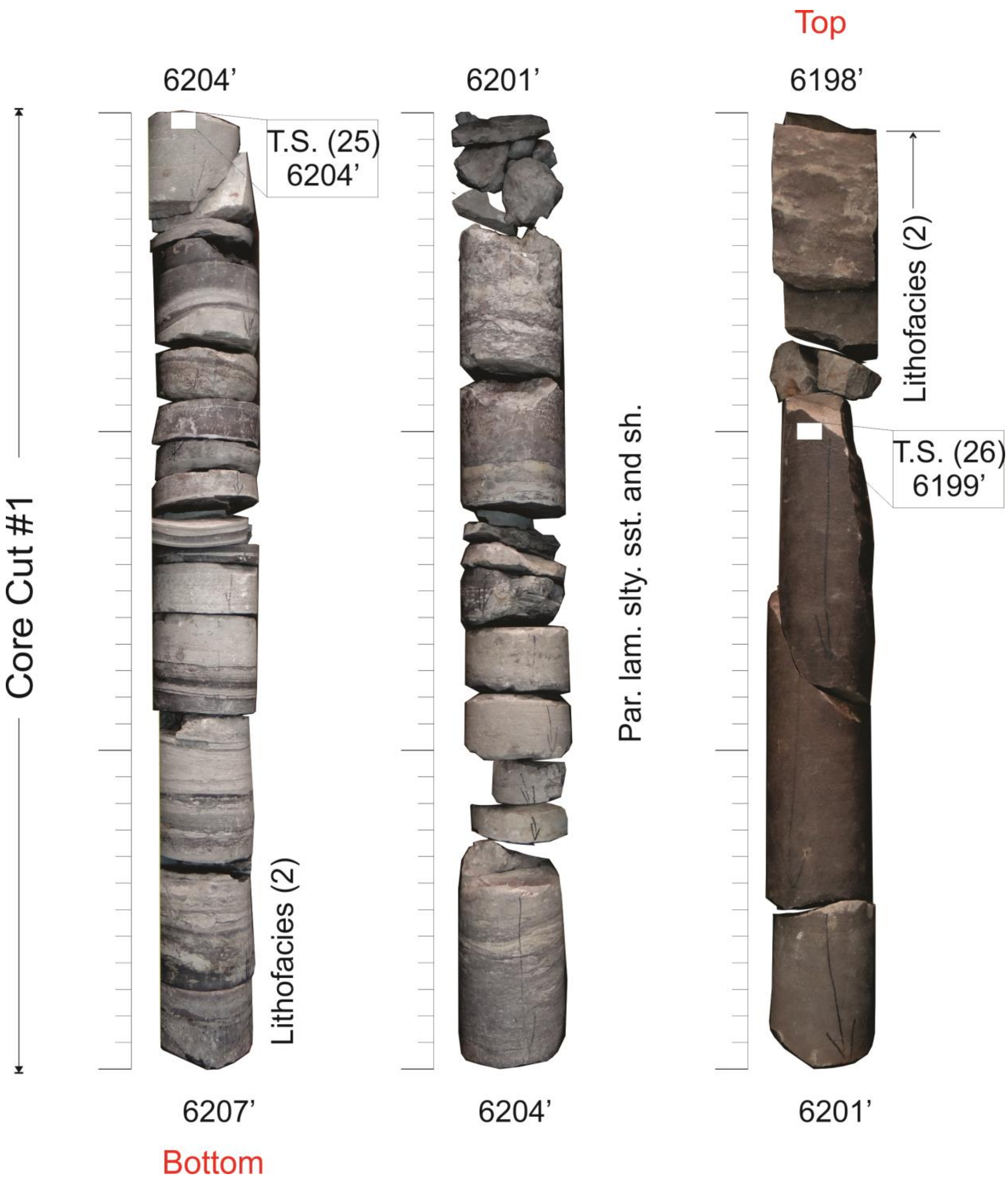
App.I.15. Detailed core description of the cored interval (5455'-5516'), showing lithofacies of Tahara Formation, in well F1-26, concession NC7A, Ghadames Basin.



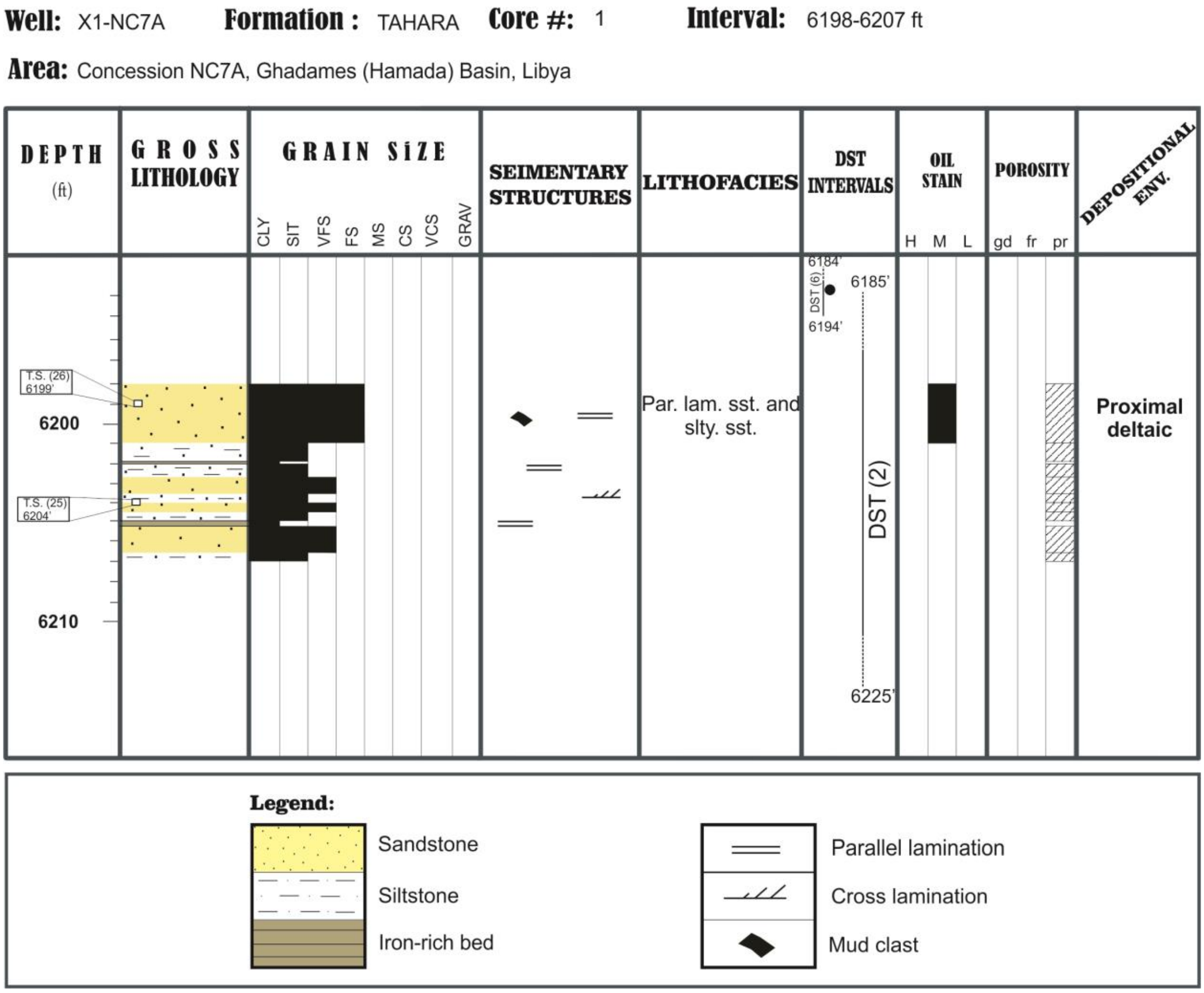
App.I.16. Photograph of cores #7 (6188’-6207’), #8 (6207’-6225’), of Tahara Formation in well M1-26, concession NC7A, Ghadames Basin. (Detailed description of lithofacies are included in App.I.17).



App.I.17. Detailed core description of the cored interval (6188'-6225'), showing lithofacies of Tahara Formation, in well M1-26, concession NC7A, Ghadames Basin.



App.I.18. Photograph of cores#1 (6198'-6207'), of Tahara Formation in well X1-NC7A, concession NC7A, Ghadames Basin. (Detailed description of lithofacies are included in App.I.19).



App.I.19. Detailed core description of the cored interval (6198'-6207'), showing lithofacies of Tahara Formation, in well X1-NC7A, concession NC7A, Ghadames Basin.

الخلاصة

هذا البحث يُقدم تفسير لبيانات سرود تسجيلات الأبار و العينات الأسطوانية و خرائط الطبقات والسحنات التحت سطحية التي تم الحصول عليها من حقل القوليبي، إمتياز م ن 7 أ, حوض غدامس، شمال غرب ليبيا. تهدف الدراسة الي استخدام طريقة سرود تسجيلات الأبار في التعرف علي السحنات الرسوبية و تتابعاتها وبيئات ترسيبها فى هذا الحقل، و معرفة العوامل الطبقية والتركيبية الممكنة التي قد تؤثر علي نشوء وحدات طبقات الحجر الرملي لتكوين الطهارة. بالإضافة الي مضاهاة الأبار واجراء تقييم لجودة سحنات المكمن.

البيئات الترسيبية القديمة فى الحقل استنتجت بجمع اتجاهات سرود اشعة جاما مع العينات الأسطوانية. تفسير السحنات اجري باستخدام تسجيلات اشعة جاما، المسامية الفعالة و المقاومة الكهربائية والتي تم الحصول عليها من 16 بئراً. واستخدمت تقنية مضاهاة الأبار لتحديد الإتجاهات التحت سطحية لهذه السحنات.

ويُظهر تعريف السحنات بأن الأبار المدروسة تتكون من رمل و سلت وطفلة. تم التعرف علي اربع اشكال لتسجيلات اشعة جاما تمثل سحنات مختلفة قد مُيزت في منطقة الدراسة: شكل القمع يمثل سحنات الشاطئ-الدلتا العليا؛ شكل جرس يمثل سحنات القنوات النهرية؛ شكل التسجيل المسنن-الشائك يمثل سحنات السلت والطفلة السفلي للمنحدرات البحرية العميقة-الحوضية و شكل التسجيل المسنن العشوائي بمقياس صغير تمثل سحنات مسطح الطين الخليجي.

ثلاث سحنات مكمنية مجتمعة في الحجر الرملي لتكوين الطهارة عرفت بناءً علي التراكيب المختلفة وانماط العمليات التحويرية، تمثل مكامن مختلفة الصفات: سحنات جيدة الجودة متزامنة مع الحجر الرملي للمرحلة الإنتقالية من الشاطئ الي الدلتا العليا بحجم حبيبات من ناعم الي متوسط بإجمالي مسامية 20% و نفاذية مقاسة من سرود الأبار 36 ملي دارسي, سحنات متوسطة الجودة متزامنة مع الحجر الرملي لقنوات الأنهار, حجم حبيبات من ناعم الي متوسط، إجمالي مسامية 12% و نفاذية مقاسة من سرود الأبار 7 ملي دارسي، و سحنات منخفضة الجودة متزامنة مع الحجر الرملي السلتي لحواف الدلتا، حجم الحبيبات من سلتي الي ناعم جداً، مع إجمالي مسامية 10% او اقل ومع نفاذية مقاسة من سرود الأبار 4 ملي دارسي. المسامية والنفاذية تكون اكثر تطوراً في مناطق طبقات الحجر الرملي المترسبة فى البيئات ما بين الشاطيئية-الدلتا.

بإستخدام نقاط تحكم الأبار المتوفرة، خرائط السمك لطبقة الرمل العلوية للسلسة السفلية لتكوين الطهارة وطبقة الرمل العلوية للسلسة العلوية لتكوين الطهارة تم التعرف عليهما و قد وضحت بأن السمك المتراكم لكلا الطبقات الرملية يعتمد علي المساحة المتوفرة لتعبئتها و درجة التضحل او التعمق للسطح الترسيبي المشترك. أيضا خرائط اقليمية لسحنات سرود الابار قد تم إنشائها لكل من طبقات الحجر الرملي المختارة وذلك لتسهيل التعرف علي توزيع السحنات الممثلة و تحديد الحدود التقريبية والمتغيرة التي تميز هذه الوحدات المدروسة لتكوين الطهارة.

الضوابط او العوامل الطبقية التي من الممكن ان تكون قد اثرت علي تطور تكوين الطهارة موضحة بشكل افضل بواسطة تغييرات مستوي سطع البحر منعكسة علي نوع السحنات الرسوبية ومعدلات ترسيبها (تغير في السمك)، خصائص التركيب المعدني لطبقات الحجر الرملي المدروسة و الإختلافات في العمليات التحويرية.

ضوابط اوعوامل تركيبية اخري من الممكن ان تكون قد اثرت علي ترسيب تكوين الطهارة متعلقة بالشكل السطحي التركيبي القديم لحقل القوليبي و الصدع الاساسي الشمالي الشرقي-الجنوبي الغربي والموازي للمستوي المحوري للنتوء المحدب لحقل القوليبي.

العوامل الطبقية والتركيبية التي تؤثر علي خصائص تكوين الطهارة، حقل القوليبي، جنوب الإمتياز م ن 7 أ، حوض غدامس، شمال غرب ليبيا.

إعداد

صالح رجب صالح بالمشكان

إشراف

د. عمر بوزيد الفقيه

قدمت هذه الرسالة استكمالا لمتطلبات الحصول على درجة الماجستير في الجيولوجيا.

جامعة بنغازي

كلية العلوم

أكتوبر 2017