Palaeozoic Petroleum Systems of the Murzuq Basin, Libya

Farid Ali Shalbak

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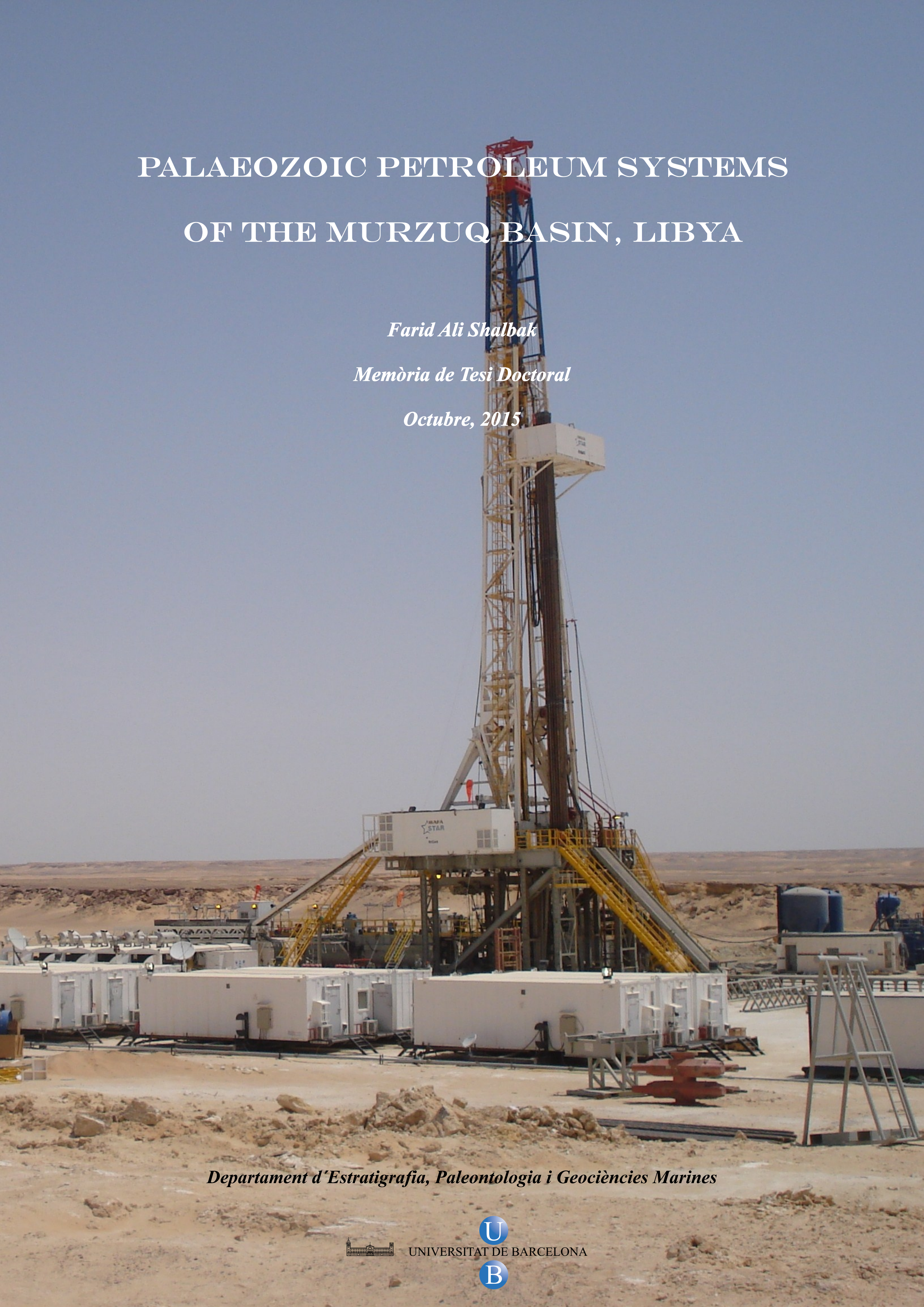

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Memòria de Tesi Doctoral

Octubre, 2015

Departament d´Estratigrafia, Paleontologia i Geociències Marines

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PALAEOZOIC PETROLEUM SYSTEMS OF THE MURZUQ BASIN, LIBYA

Memòria de Tesi Doctoral presentada per
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per a optar al títol de Doctor en Geologia per la Universitat de Barcelona

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Contents:

LIST OF ABBREVIATIONS:

AOM = *Amorphous organic matter*

BB = *Barrels*
BBB = *Billion barrels*
BBC = *Billion barrels of condensate*
BBO = *Billion barrels oil*
BBOE = *Billion barrels oil equivalent*
BC = *Barrels of condensates*
BC/D = *Barrels of condensates per day*
BCM = *Billion of cubic meters*
B/D = *Barrels per day*
BOE = *Barrels oil equivalent*
BOE/D = *Barrels oil equivalent per day*
BW/D = *Barrels of water per day*

CF = *Cubic feets*
CM = *Cubic meters*

MBB = *Million barrels*
MB/D = *Million barrels per day*
MBOE = *Million barrels oil equivalent*
MCM = *Million of cubic meters*
MMSTB = *Million stock tank barrels*

R/P = *Reserves-production ratio*

TBB = *Trillion barrels*
TCF = *Trillion of cubic feets*
TCM = *Trillion of cubic meters*
TOC = *Total organic carbon*

ABSTRACT:

The Murzuq Basin is a sedimentary basin about 800 x 800 km large, covering an area of over 350,000 km^2 located in the south and southwest of Libya. It has a relatively continuous Palaeozoic sedimentary infill, although actually most of the basin is covered by Mesozoic strata and Holocene sand dunes forming the Libyan Desert. The Murzuq Basin is a frontier area which has remained sparsely explored until the last decades. Petroleum exploration in the Murzuq Basin began in 1957, and in the last 25 years significant oil accumulations have been discovered, having greatly increased the interest for the area's potential. The last oil in place estimation for the Murzuq Basin resources is about 6.0 BBB of oil and about 1.0 TCM of gas, which represent about 6.5% of the Libya's resources. The larger probed reserves in the Murzuq Basin are located in the NC115, NC174, NC186 and NC210 blocks. Production in the Murzuq Basin began in late 1996, when the giant El Sharara Field comes on stream; nowadays El Sharara Fiel is capable to produce up to 200,000 B/D. About the 30% of the Libya's current oil production is supplied by the Murzuq Basin.

Geologically the Murzuq Basin is an erosional remnant of a much larger Palaeozoic continental margin rimming Gondwana. The present-day flanks of the basin are defined by erosion resulting from multiphase tectonic uplifts; consequently the current basin geometry has not relation to the broad and large peri-Gondwana continental margin which existed in the area during Palaeozoic times. The Murzuq flanks comprise the Tihemboka, Tibesti, Gargaf and Atshan highs. The basin is filled by a thick Palaeozoic sedimentary succession of marine and transitional sediments deposited on a neo Proterozoic to Precambrian basement. Marine and non-marine Mesozoic deposits also are present. In general sedimentation rate during Palaeozoic times was low in the Murzuq Basin and their maximum sedimentary infill reaches about 3000 metres in thickness. The sedimentary infill of the basin records several generations of structuring, mainly compressional and transpressional in nature, but the cumulative structural deformation is considered relatively minor. Although fault arrangement displays considerably variations, a N-S trend is dominant.

In this work the Palaeozoic sedimentary infill of the Murzuq Basin is divided in fifteen lithostratigraphic units called from older to younger: Hasawnah, Achabiyat, Hawaz, Melaz Suqran, Mamuniyat, Bir Tlacsin, Tanezzuft, Akakus, Tadrart, Wan Kasa, Awainat Wanin, Marar, Assedjefar, Dembaba and Tiguentounine formations. The older Hasawnah Fm records an initial marine transgression during late Cambrian to middle Ordovician times and the younger Tiguentounine Fm records deposition during the late Carboniferous to lowermost Permian times. Generally Permian rocks are missing in the Murzuq Basin because during this period the main phase of Hercynian uplift and erosion took

place and most of the Permian strata were removed.

A set of major basin-scale unconformities are recognized within the sedimentary infill recording the orogenic history and other major geological processes occurred in the Murzuq Basin which, in turn, controlled deposition. These basin-scale unconformities allow us the stratigraphic subdivision of the Palaeozoic sedimentary record into four second order sequences. The main basin-scale unconformities are the Pan-African, Taconian, Caledonian and Hercynian tectonic phases and the Late Ordovician glaciation. Other unconformities which could be recognized within the sedimentary record are minor or belong to the younger Austrian and Alpine cycles, and consequently, they don't affect the deposition of the Palaeozoic sequences.

The Hawaz and Mamuniyat formations are two siliciclastic units late Ordovician in age mainly made of quartzarenites with moderate to good reservoir properties which constituted the most prolific reservoir units in the Murzuq Basin. All the commercial findings in the basin are reservoired within these two units. Locally however, porosity and permeability values of the Hawaz and Mamuniyat sandstones widely ranges as a consequence of facies variations, sedimentary barriers and diagenetical processes, but most of these sandstones have good porosity and permeability characteristics. For the Hawaz sandstones porosity values up to 25.7% have been measured although porosity values around 15 to 16% are the most frequent. Pore connectivity is good, and pore diameter ranges from 0.1 μm to 64 μm (average 14.6 μm). Permeability values up to 900 to 1000 mD have been measured in core plugs from the Hawaz sandstones. Mamuniyat sandstones show a regional trend of their reservoir properties. The poorer porosity values are located around the central part of the basin, usually reaching less than 5%, whereas towards the West, North and East the formation clearly increases their porosity. Maximum porosity values have been reported from the southwestern margin, near Ghat, where porosity reach up to 25%. Analogously permeability widely changes, but values up to 1850 mD have been measured in well A1-NC115.

A second target in the Murzuq basin may be related to the Basal Devonian Sandstones (BDS) reservoir, a basal Member of the middle to late Devonian Awainat Wanin Fm. Although generally the BDS displays poor reservoir properties, locally it may reach fair reservoir quality. However, it must be highlighted that to date, all the Murzuq discoveries reservoired within the BDS interval have resulted non commercial.

The Murzuq Basin contains a number of fine-grained organic-rich units having moderate to high TOC content and potentially able to generate hydrocarbons as the early Silurian Tanezzuft Fm and their basal Hot Shale Mb, the middle to late Devonian Awainat Wanin Fm including the fine-grained intervals within the BDS or the early Carboniferous Marar Fm. However, the unique proved source rock in the Murzuq Basin is the basal Tanezzuft Hot Shale Mb.

For the remainder units their significance as effective source rocks in the Murzuq Basin has not been proven to date and their contribution to discoveries is speculative.

The Hot Shales reported the highest TOC values in the Murzuq Basin, with TOC contents ranging from 3.0 to 15%, although extreme values up to 23.3% have been measured. The organic-rich Hot Shale facies contain mainly Type II oil-prone kerogen and they are characterized by good pyrolisis-related hydrocarbon generative potential such as Hydrogen index (HI) and S2. HI values range between 50 and 400, although most of the samples have values lowers than 175. Usually S2 values reach up to at least 60 mg HC/g rock and probably up to 100 mg HC/g rock for the best samples, both indicative of very good initial source potential. Rock-eval pyrolisis supplied Tmax values mostly in the range of 430ºC – 446ºC where is located the main oil window, and clearly increase with increasing depth. On the other hand, immature to early mature conditions are reported locally (i.e. by samples from west and southwest of NC187 concession). The inferred Tmax maturity levels are in agreement with other measured maturity parameters as vitrinite reflectance and spore colour index. The kerogen components have been analysed by counting 200 particles by sample. Amorphous organic matter (AOM) is the main kerogen component, constituting over 80%; phytoclasts and palynomorphs are subordinate components. This composition is a characteristic assemblage of a type II kerogen.

Oil has low density, with API degrees ranging between 31.8 and 40.9 and mostly must be classified as light oils.

All the commercial finds in the Murzuq Basin have the thick and shaly Tanezzuft Fm as top seal. The sealing capacity of the Tanezufft shales is generally good, especially in the distal areas where the formation is finer-grained. Locally, when the Tanezzuft Fm deposited over some paleohighs or southwards, in a more proximal location, the Tanezzuft Fm becomes sandy, with a poorer sealing capacity. The most silty composition of the Tanezzuft shales, and therefore their better sealing capacity, correspond with the central and northern parts of the Murzuq Basin. Eastwards the Caledonian unconformity produces truncation of the Tanezzuft shales and the formation thins and is removed. In these areas the Hawaz or Mamuniyat reservoirs may be capped by Devonian strata with variable sealing capacities, but the lack of Devonian commercial oil discoveries could be interpreted as the result of ineffective sealing capacity of the Devonian sequences. In some structures, as in the Hawaz buried hills lateral seal is provided by the fine-grained Melaz Suqran and Bir Tlacsin formations.

Four trap types have been described in the Ordovician reservoirs of the Murzuq Basin: Hawaz “buried hills”, lateral pinch-out of the Mamuniyat sandstones, single anticlines and antiform structures, and lateral closure by different fault types. The first two trap types are related to the palaeotopographic surface developed during the Upper Ordovician glaciation and the second two are structural traps.

Buried hills were originated by erosion of the ice sheet or subglacial meltwater during late Ordovician glaciation on the middle Ordovician sequences, creating a topography of highs and lows; these highs are often made up by the Hawaz sandstones and provide effective traps for the proven oil accumulations. The intervening paleovalleys are filled by the Mamuniyat Fm. Both, Hawaz and Mamuniyat sandstones are reservoirs and they are in lateral contact with the Hot Shale source and vertically overlied by the Tanezzuft seal. This is the most prolific and common trap type in the Murzuq basin. Stratigraphical pinchouts of the Mamuniyat sandstones filling the paleovalleys is also a relatively frequent trap. Both, buried hills and pinchouts are the older traps in the basin. Structural traps are scarce and limited to Caledonian and Hercynian anticlinnal and faulted anticlinal structures.

Two Palaeozoic petroleum systems have been identified within the Murzuq Basin. Both involving the early Silurian Hot Shale source: **a)** A late Ordovician petroleum system composed of the Hawaz/Mamuniyat sandstones reservoir, the Hot Shale source and the Tanezzuft seal, and **b)** A middle Devonian petroleum system composed of the BDS sandstones reservoir, the Hot Shale source and intra Devonian shales seal.

In the late Ordovician petroleum system oil was expelled from the Hot Shales directly into the underlying Hawaz and Mamuniyat sandstones, which contain all the commercial discoveries in the Murzuq Basin. So, oil migration was short and reservoir recharge laterally. Results of basin modelling suggest timing of petroleum generation and trapping from late Carboniferous to Cretaceous or even early Tertiary. This system is the primary play in all the commercial oil discoveries in the northern and central part of the Murzuq Basin and their resources in the Murzuq Basin are estimated more than 2000 MMSTB.

The Devonian system is a secondary potential petroleum system constituted by the middle Devonian BDS sandstones reservoir charged indiscriminately by both, Devonian or Silurian organic-rich shales and sealed by intra Devonian shaly intervals. The possible existence of the Devonian system is supported by the discovery of some non commercial oil accumulations and the presence of frequent oil shows in the BDS interval. However, to date commercial finds has been not recorded within the Devonian system and their hydrocarbon potential remains poorly understood.

RESUMEN:

La Cuenca de Murzuq tiene unas dimensiones aproximadas de 800 x 800 km y ocupa una extensión de unos 350.000 km^2 en el sur y suroeste de Libia, limitando con Argelia y Nigeria. La cuenca contiene un registro Paleozoico relativamente continuo a su vez recubierto por una potente secuencia Mesozoica y de dunas eólicas actuales que constituyen el denominado Desierto Líbico, una parte del Desierto del Sahara. Dadas sus condiciones extremas la exploración de la Cuenca de Murzuq ha permanecido poco desarrollada hasta las últimas décadas. De hecho la exploración petrolera en la Cuenca de Murzuq no se inició hasta el año 1957, pero la cuenca ha demostrado ser muy prolífica y en los últimos 25 años se ha producido el descubrimiento de importantes campos petrolíferos, lo que ha aumentado significativamente el interés por el potencial de la misma. Las estimaciones más recientes calculan unos recursos del orden de los 6 billones de barriles de petróleo y de 1 trillón de m^3 de gas en la cuenca, lo que representa aproximadamente el 6,5% del total de los recursos de Libia. Actualmente las mayores reservas de la Cuenca de Murzuq se centran en las concesiones NC115, NC174, NC186 y NC210. La producción comercial de petróleo en la Cuenca de Murzuq se inició a finales del año 1996 con la puesta en funcionamiento del yacimiento gigante de El Sharara, capaz de producir hasta 200.000 barriles/día. En la actualidad la producción de la Cuenca de Murzuq supone el 30% de la producción total de Libia.

Geologicamente la Cuenca de Murzuq es un resto debido a la erosión multifase producida sobre un margen continental que durante el Paleozoico bordeaba el supercontinente de Gondwana. Los límites actuales de la cuenca son bloques tectónicamente elevados durante las orogenias Caledonica, Hercínica y sobre todo, Alpina, por lo que la actual geometría de la cuenca no guarda ninguna relación con el extenso margen continental que se extendía bordeando Gondwana durante el Paleozoico. Los bloques elevados que constituyen los actuales límites de la cuenca son los macizos (también llamados arcos en la literatura) de Tihemboka y Tibesti por el SW y SE respectivamente y los de Gargaf y Atshan que la delimitan por el N. La cuenca está rellena por una potente sucesión Paleozoica dominantemente constituida por sedimentos siliciclásticos que registran la sedimentación en ambientes marinos y transicionales y que se depositaron sobre un basamento de edad Neoproterozoico a Precámbrico. Superpuesta a la sucesión Paleozoica existe también una potente sucesión Mesozoica que queda fuera del objetivo de esta Tesis; las rocas Mesozoicas no están presentes en los altos estructurales que delimitan la cuenca. La tasa de sedimentación durante el Paleozoico fue, en general, baja. El máximo espesor de la sucesión Paleozoica es del orden de los 3000 m. El análisis de las estructuras que afectan al registro sedimentario de la Cuenca de Murzuq permite reconocer la existencia de diversas fases de deformación tectónica, principalmente de carácter compresivo y transpresivo, sin embargo

se considera que la deformación total acumulada es relativamente poco importante. Las fallas tienen direcciones muy variables, aunque las direcciones N-S son dominantes.

La totalidad del registro Paleozoico se ha subdividido en quince unidades litoestratigráficas, que de más antigua a más moderna son: Fm Hasawnah (Cámbrico Superior – Ordovícico Inferior); Fms Achabiyat y Hawaz (Ordovícico Medio – Superior); Fms Melaz Suqran, Mamuniyat y Bir Tlacsin (Ordovícico Superior); Fm Tanezzuft (Silúrico Inferior), esta Fm contiene un Miembro basal denominado Hot Shale Mb; Fm Akakus (Silúrico Medio – Superior); Fms Tadrart y Wan Kasa (Devónico Inferior); Fm Awainat Wanin (Devónico Medio – Superior), esta unidad contiene un miembro basal conocido en la literatura como BDS; Fms Marar y Assedjefar (Carbonífero Inferior); Fm Dembaba (Carbonífero Superior), esta unidad es la primera unidad Paleozoica constituida en parte por carbonatos y Fm Tiguentounine (Carbonífero Superior – Pérmico basal). En general no existe registro Pérmico en la Cuenca (o está muy incompleto) debido a que se considera que la principal fase de denudación ligada a la fase Hercínica se produjo durante este período de tiempo. La Fm Hasawnah que constituye la base de la sucesión Paleozoica registra una primera transgresión marina sobre el margen continental de Gondwana.

Aunque el registro Paleozoico es relativamente continuo, existen no obstante una serie de discontinuidades reconocibles a escala de cuenca que son el resultado de los movimientos orogénicos y otros procesos geológicos principales que afectaron a la totalidad de la cuenca y que a su vez, condicionaron la sedimentación. Estas discontinuidades regionales han permitido la subdivisión del registro sedimentario en cuatro secuencias de 2º orden. Las principales discontinuidades regionales son las que se corresponden con los eventos tectónicos Pan-Africano, Caledonico y Hercínico (U_0, U_5 y U_8 respectivamente en este trabajo), además de la superficie erosiva relacionada con la glaciación del Ordovícico Superior (U_2). Entre el registro sedimentario se pueden reconocer otras discontinuidades, pero o bien son de carácter local o bien se relacionan con ciclos tectónicos más tardíos y en consecuencia no afectaron a la sedimentación Paleozoica.

De totas las unidades anteriormente reseñadas las Fms Hawaz y Mamuniyat constituyen el principal reservorio en la Cuenca de Murzuq y la totalidad de los yacimientos comercialmente explotables de la cuenca se localizan en estas rocas almacén. Ambas son unidades siliciclásticas del Ordovícico Medio y Superior que están dominantemente constituidas por cuarzoarenitas. De manera general presentan unas buenas propiedades como roca almacén, aunque puntualmente y como consecuencia de las variaciones de facies o de la existencia de barreras sedimentarias o diagenéticas, sus valores de porosidad y permeabilidad pueden verse muy modificados. Sin embargo la mayor parte de las areniscas de las Fms Hawaz y Mamuniyat presentan valores adecuados de porosidad y permeabilidad. En las cuarzoarenitas de la Fm Hawaz se han medido valores de la porosidad de hasta el 25,7% aunque los valores más frecuentes oscilan entre el 15 y el 16%. La conectividad entre poros es buena y el tamaño de poros medido varía entre 0,1 mm y 64 mm, con un valor promedio de 14,6 mm. En muestras de testigos de esta formación se han medido valores de permeabilidad de hasta 900 y 1000 mD. Las cuarzoarenitas de la Fm Mamuniyat presentan una tendencia regional en sus propiedades petrofísicas. Los peores valores en la porosidad se encuentran aproximadamente en la parte central de la cuenca, donde son frecuentes porosidades de menos del 3%; sin embargo estos valores tienden a aumentar desde el centro hacia el Oeste, Norte y Este, alcanzando los mayores valores promedio hacia la zona SO de la cuenca, cerca de la localidad de Ghat, donde se han medido porosidades de hasta el 25%. De la misma manera, los valores de la permeabilidad también varían con una tendencia similar. Valores de la permeabilidad de hasta 1850 mD han sido medidos en muestras del sondeo A1-NC115.

En base a sus propiedades petrofísicas, los intervalos areniscosos del Mb BDS podrían ser considerados en determinadas ocasiones como un reservorio secundario para la Cuenca de Murzuq. Sin embargo debe de considerarse que aunque localmente estas areniscas poseen muy buenas propiedades como roca almacén, superiores incluso a las de las cuarzoarenitas de las Fms Hawaz y Mamuniyat, esto solo se da de manera muy puntual y generalmente las areniscas del BDS poseen unas propiedades petrofísicas relativamente pobres. Adicionalmente debe de remarcarse que todos los descubrimientos realizados hasta la fecha en el BDS han resultado con muy baja producción y no explotables comercialmente.

La sucesión Paleozoica de la Cuenca de Murzuq contiene varias unidades detríticas finas ricas en materia orgánica y capaces de generar hidrocarburos. Estas unidades son la Fm Tanezzuft incluyendo su miembro basal Hot Shale Mb, los intervalos arcillosos interestratificados en la Fm Awainat Wanin o la Fm Marar. De entre todas ellas la única de eficacia probada como roca madre son las arcillas del Mb Hot Shale. Para el resto de las unidades su papel como rocas almacén no ha sido demostrado y su posible contribución a los yacimientos descubiertos hasta la fecha es especulativa.

Las arcillas del Mb Hot Shale contienen los mayores valores de TOC en la Cuenca de Murzuq, con contenidos en TOC que normalmente varían entre el 3 y el 15%, aunque excepcionalmente se han medido valores de hasta el 23,3%. Las arcillas ricas en materia orgánica del Hot Shale Mb contienen principalmente kerógeno de tipo II y se caracterizan por presentar unos parámetros que indican un elevado potencial como generador de hidrocarburos, principalmente el índice de Hidrógeno (HI) y el pico S2. Los valores de HI medidos mediante ensayos de pirólisis varían entre 50 y 400, aunque la mayoría de las muestras presentan un HI menor de 175. Normalmente los valores de S2 sobrepasan los 60 mg HC/g de roca, llegando en las mejores muestras hasta los

100 mg HC/g de roca. Los rangos de valores obtenidos para ambos parámetros son indicadores de un excelente potencial como roca madre. Los valores de Tmax obtenidos mediante pirólisis quedan, en su mayoría, dentro del rango de la ventana del petróleo; esto es, entre los 430º C y los 446º C y muestran un claro incremento con la profundidad. Localmente, p.e.: en muestras de sondeos del oeste y suroeste de la concesión NC187, se han obtenido valores que quedan en el rango de los kerógenos inmaduros. Los niveles de maduración obtenidos mediante los ensayos de pirólisis (Tmax) están de acuerdo con los aportados mediante la utilización de otros indicadores como la reflectividad de la vitrinita o el índice de color de las esporas, que también han sido obtenidos. Se han analizado los componentes de los kerógenos mediante el contaje de 200 partículas por muestra; de ellos, el componente principal es la materia orgánica amorfa (AOM) que representa hasta el 80% de los componentes. Los fitoclastos y los palinomorfos son componentes muy minoritarios. Esta composición dominada por la presencia de AOM es característica de los kerógenos de tipo II.

En general el petróleo derivado de esta roca madre es de baja densidad, con valores de entre 31,8 y 40,9 grados API, por lo que deben de ser clasificados como petróleos ligeros.

En cuanto a la roca de sellado, la totalidad de los campos explotados comercialmente tienen como sello superior la potente Fm Tanezzuft. Las propiedades como roca de sellado de la Fm Tanezzuft son generalmente buenas o muy buenas, especialmente hacia las zonas más distales donde la Fm es más arcillosa; sin embargo en zonas más proximales con una cierta proporción de limos y arenas la capacidad de sellado de la Fm disminuye. Las mejores propiedades como roca de sellado se dan en la zona central y Norte de la Cuenca de Murzuq, mientras que las peores propiedades se producen hacia el Sur de la Cuenca y sobre los principales altos. Hacia el Este de la Cuenca la Fm Tanezzuft queda afectada por la superficie erosiva Caledónica, por lo que en esa dirección la Fm se adelgaza y finalmente desaparece. En estos casos las cuarzoarenitas de las Fms Hawaz y Mamuniyat pueden quedar truncadas por las secuencias del Devónico que poseen una capacidad de sellado muy variable. En algunas estructuras muy típicas como los denominados “*Buried hills*” las Fms Melaz Suqran y Bir Tlacsin proporcionan el necesario sello lateral.

Hasta cuatro tipos de trampas han sido reconocidas en el subsuelo de la Cuenca de Murzuq: Los ya citados “*Buried hills*”, acuñamientos laterales de las areniscas de la Fm Mamuniyat, estructuras anticlinales y antiformes y trampas ligadas a distintos tipos de fallas y anticlinales fallados. Los dos primeros tipos se relacionan con la paleotopografia resultante de la erosión producida por la glaciación del Ordovícico Superior mientras que los dos segundos tipos son trampas estructurales.

Los “*Buried hills*” son los relieves resultantes tras la erosión producida por el hielo o por el agua subglaciar durante la glaciación del Ordovícoco Superior, que originó una paleotopografía constituida por valles encajados entre altos relativos. Los altos estaban principalmente constituidos por sucesiones de la Fm Hawaz. Posteriormente los paleovalles fueron rellenados total o parcialmente por la sucesión de las Fms Melaz Suqran, Mamuniyat y finalmente Bir Tlacsin. Los altos constituidos por cuarzoarenitas y sellados lateralmente por las Fms Melaz Suqran y Bir Tlacsin, y a techo por la Fm Tanezzuft produjeron trampas eficaces para la acumulación de petróleo. El relleno de los valles dio lugar, en algunos casos, al acuñamiento lateral contra las paredes de los paleovalles de las areniscas de la Fm Mamuniyat que a su vez quedaron intersetratificadas entre las impermeables Fms Melaz Suqran, y Bir Tlacsin, dando lugar así al segundo tipo de trampa. Estos dos tipos de trampa son los más antiguos en la Cuenca de Murzuq, y especialmente en las zonas centro y Norte de la cuenca, los más frecuentes. Las trampas estructurales no son muy frecuentes y se limitan a estructuras anticlinales y antiformes ocasionalmente asociados a algún tipo de falla que le proporciona sello lateral; estas estructuras son de edad Caledonica o Hercínica.

En la Cuenca de Murzuq se han identificado dos sistemas petroleros Paleozoicos. En ambos la roca madre son las Hot Shale del Silúrico basal. Estos sistemas son: **a)** Un sistema petrolero del Ordovícico Superior constituido por las areniscas de las Fms Hawaz y Mamuniyat como reservorio, las Hot Shale como roca madre y la Fm Tanezzuft como roca de sello, y **b)** Un sistema petrolero del devónico Medio constituido por los tramos areniscosos del BDS como reservorio, las Hot Shale como roca madre y los diversos intervalos lutítico -arcillosos intra Devónicos como roca de sellado.

En el sistema petrolero del Ordovícico Superior existe un contacto directo tanto vertical como en ocasiones lateral entre la roca madre y el reservorio. En estos casos el petróleo fue expelido directamente desde las Hot Shales hasta las infrayacentes areniscas de las Fms Hawaz y/o Mamuniyat, por lo tanto la migración fue corta, como cabe esperar en cuarzoarenitas de este tipo, y el reservorio fue recargado lateralmente. Los modelos realizados para deducir la historia térmica y edad de generación de los hidrocarburos muestran grandes diferencias, habiéndose obtenido edades que van desde el Carbonífero Superior al Cretácico o incluso el Terciario basal. Muchas de estas discrepancias provienen de la disparidad en los datos de partida, especialmente en lo que se refiere a la magnitud de exhumación y denudación sufrida durante los eventos tectónicos Caledónico, Hercínico y Alpino, que deberían ser revisados. Este sistema petrolero es el que contiene la totalidad de los campos en producción en la Cuenca de Murzuq y se le estiman unas reservas para las zonas central y Norte de la cuenca de más de 2000 MMSTB

El sistema petrolero Devónico es un sistema secundario que solo debe de ser considerado como potencial. Está constituido por las areniscas del BDS como roca almacén, como roca madre podrían contribuir indistintamente las

Hot Shales o los intervalos arcillosos ricos en materia orgánica interestratificados entre la Fm Awaynat Wanin, y el sello sería proporcionado por los mismos intervalos arcillosos intra-Devónicos. La posible existencia de este sistema petrolero Devónico queda demostrada por el descubrimiento de algunos yacimientos no comerciales y por la presencia de abundantes “oil shows” entre las areniscas del BDS. Sin embargo, hasta la fecha no se ha descubierto ningún campo comercialmente explotable en este sistema petrolero y su potencial no está claramente definido.

1. INTRODUCTION

1.1 INTRODUCTION:

Murzuq is a remote Paleozoic sedimentary basin located in the south and southwest of Libya. Most of the basin is covered by sand dunes, forming a thick sand sheet know as the Libyan Desert as a part of the Sahara Desert. Due to its difficult terrain, the Murzuq Basin results expensive to explore and this frontier area has remained sparsely explored until the last decades.

However, the increase of purchase price of oil along last years and the expected maintenance (although with fluctuations) of high rates for the next years, allowed to the oil industry to have more resources to put in exploration, even in remote areas with expensive exploration rates. Furthermore, the new role played by the Libyan government and the consequent opening of the country to the foreign oil companies at the end of the past century, had increased the interest in the zone. The recent auctions bid round of Libyan concessions have counted with the concurrence of a growing number of European and American companies. As a consequence, and despite the political instability arises by the Arabic spring during the last three years and the present-day instability, it will be expected that the Murzuq Basin will deserve an active exploration campaign by the oil industry during next years, when political stability becomes again.

As a result of this interest, a set of monographic papers updating the status of the knowledge of the surface and subsurface geology have been published in the last decade. The main of them, total or partially concerning the Paleozoic petroleum systems in Murzuq, are the works by MacGregor et al. (1998), Sola and Worsley (2000), Hallet (2002), Salem (2003), Arthur et al. (2003) and Salem et al. (2012).

1.1.1. Exploration history:

The exploration history of the Murzuq Basin is linked to the exploration history in Libya and North Africa. The first exploration well in North Africa was drilled as early as 1892 in Northern Algeria, but it was not until 1909 that the first commercial oil discovery was made in Gemsa, in the Egyptian coast of Suez. This produced small quantities of oil from Miocene reservoirs. In Libya, exploration started in 1901 by Italian geologists, which studied the coastal region of Cyrenaica, and the first geological map of Libya was published by Vinassa de Regni in 1912. The exploration centred on the Paleozoic sequences started after the recognition, in the decades 1930's and 1940's of the presence in North Africa of large Paleozoic basins, potentially prospective for hydrocarbons.

During the initial exploratory period of North Africa, immediately after the Second World War, some National Oil Companies were created (eg. the Algerian SNREPAL), and operators studied the region and carried out field works, although these works mainly focused on the Mesozoic and Tertiary of Algeria. After this initial period, a number of fields were defined and, during the years 1953 to 1956 up to 50 wells were drilled and up to 12 findings were made. In these three years - called by Traut et al. (1998) the "initial discovery period" – were discovered the Hassi Messaoud oil field, in the Cambro-Ordovician of northwestern Ghadamis Basin, with initial estimated recoveries up to 10 BBOE, and the Hassi R'Mel Field, in the Triassic Northern of Oued Mya Basin, with estimate reserves of 90 TCF of gas and 3 BBC, both in Algeria.

After 1956, and during a period lasting approximately up to 1964, the exploration in North Africa was at its peak. During these 7-8 years, a total of 457 exploration wells were drilled, and up to 143 discoveries made. In this period, recoverable reserves were estimated in 11 BBOE, and exploration was centred mainly, but not only, in the Illizi and Ghadamis Basins. Other areas including Libyan Basins also were explored. So, in 1957 Exxon drilled the Astan B2.1 well, the first oil discovery in Libya, it matches with Devonian sandstones and were located at the Astan Arch. But interest into exploration Libyan's basins moving to the Northern Hamra Basin, were a number of discoveries as Bir Tlacsin and Tigi fields in the northern part, Gazeil and Z-1-66 fields in the central part, and El-Hamra Field to the South were made between 1959 and 1961. However, all these discoveries produced small oil quantities, and the discovery by the Esso's C1-6 well in 1959 of the Zelten giant Field, hosted in the Tertiary of the Sirte Basin, shifted the exploratory interest to the central part of Libya.

Approximately by 1965, this trend characterized by high exploration effort changes owing to a series of political affairs. In 1963 the recently independent Democratic Republic of Algeria created the state company SONATRACH in order to manage exploration and production of oil industry, and a nationalization process started. In Libya, a change in the Government was produced in 1969, laying down a new Constitution. According to, a gradual nationalization process of the foreign oil companies - completed in 1973 - was caused. These successes make that, approximately after 1965, the exploration effort in North Africa decayed. This situation, known by some authors as “post boom period”, has been kept until 1985. Spite this, during these 20 years of post boom period up to 425 exploration wells were drilled, and 117 discoveries were made in North Africa, which increased the total reserves more than 4,4 BBOE. During this period, exploration activity in Libya was centred in the western part, and small finds were made in the Hamra Basin.

In 1976, in the shallow waters of the Gabes Gulf, at 170 m water depth, AGIP discovered the offshore Bouri Field in block NC-41, the field holds around 670 MBB oil and 670 BCM of gas, resulting the larger offshore field in the Mediterranean sea.

In 1986 the situation changed, mainly does to political changes in Algeria and Libya, producing a reactivation in the exploration and production tasks. The Algerian’s hydrocarbon legislation was deeply modified in 1986, at this time, the first commercial discoveries were made by ROMPETROL and Bulgarian oil Companies in Murzuq Basin, allowing to foreign companies to operate in the country under more profitable conditions. This opening of the two most important oil producing countries in North Africa has been reached in parallel with a major improvement of their transport and production infrastructures. Gas production in Algeria was improved with new installations and facilities to liquidize gas as well as the building of two pipelines across the Mediterranean, from the northern coast to Italia (1981) and Spain (1996). In Libya, two pipelines from Murzuq Basin to Zawia and from Wafa to Mellita, both in the Mediterranean coast, was finished in 1996 and 2001 respectively.

The coming in of foreign companies together with the technological improvement resulted in an important increasing in discoveries and reserves in North Africa. Between 1986 and 1998 a total of 171 exploration wells were drilled, and 63 discoveries were made, supplying 4.1 BBOE of additional reserves (Traut et al, 1998). The most important new finds made after 1986 in North Africa are located in the Ghadamis, Hamra, Sirte and Murzuq Basins.

Exploration in Murzuq basin:

Petroleum exploration in the lightly-explored and sand-dune ridden Murzuq Basin started in 1957 using poor seismic data and unsophisticated testing techniques, but this effort led to discoveries in the last 25 years of economically significant oil accumulations in NC-115, NC-174, NC-186 and NC-101 (see Fig. 1), having greatly increased interest for the area's potential. The exploration history of the Murzuq Basin can be divided in three stages or periods:

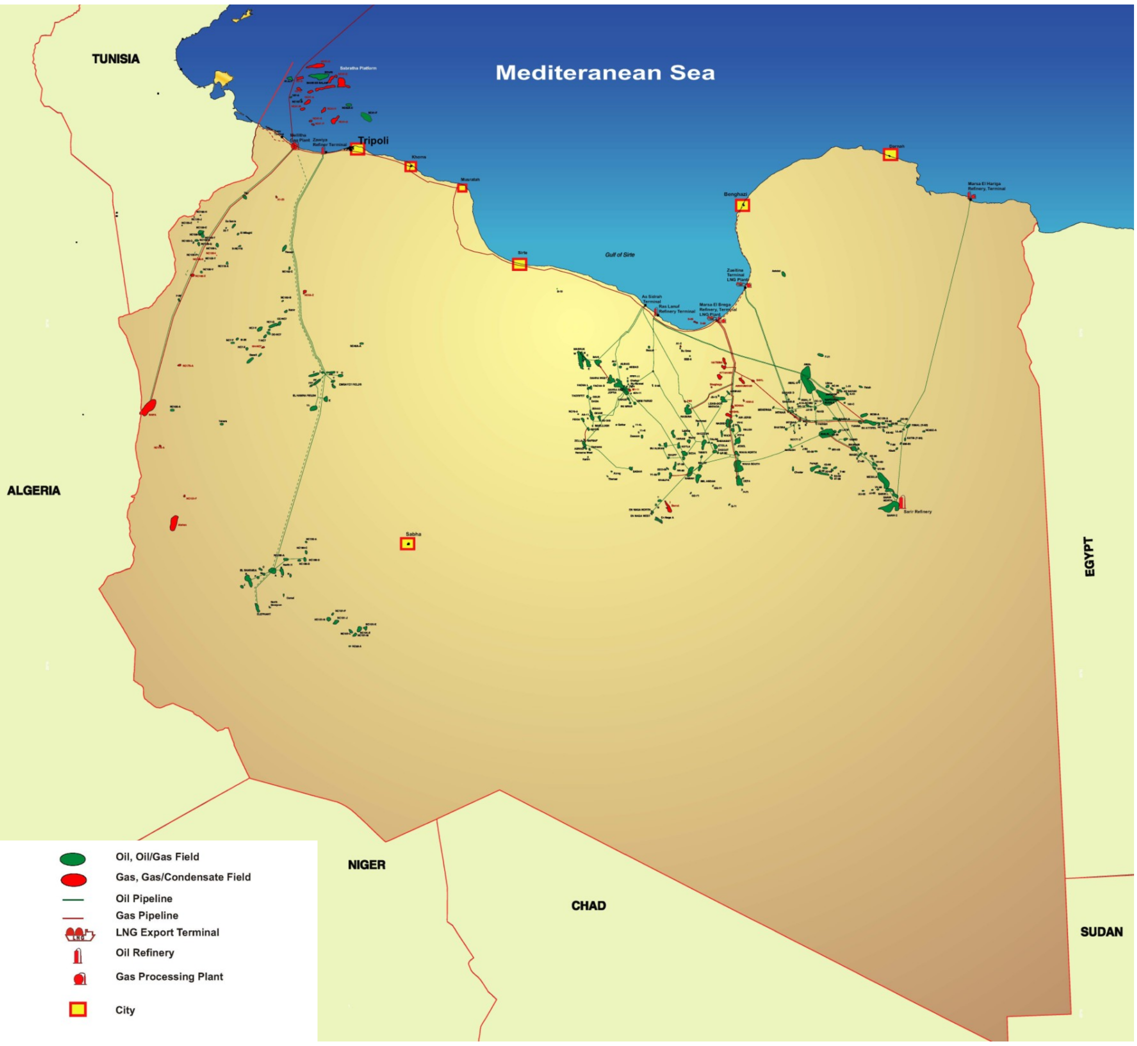


Figure 1.- Schematic geological map of Libya showing the location of the main Palaeozoic basins and the oil and gas fields of Libya and surrounding regions.

During an initial period (1957-1968) a number of wells were drilled in the Astan Arch, in the north-eastern border of the basin, leading to the discovery of the Astan gas field. Furthermore, five wells were also drilled southward, in the basin, of which the A1-76 well, drilled by PANAM in 1959, tested oil in the Devonian rocks.

A second period (1970-1985) started with the drilling by Occidental of the well A1-NC34, and included significant exploration efforts by several other companies. Successful exploration efforts by ROMPETROL in NC115, and BOCO in NC101 led to the first economic oil discoveries in the Cambro-Ordovician rocks or northern Murzuq Basin. Extensive but unsuccessful exploration program was completed by BRASPETRO in NC58 in the southern part of the basin. The program included the drilling of eight wells, one of them, the A1-NC58 well, detected some oil accumulations in the Tahara Formation (Upper Devonian).

The third period, since 1990 until the present, mainly centred the exploration efforts at the NC58, NC101, NC115 NC174, NC186 and NC210 blocks, resulting the most notable for the successful exploration. In October 1997 an international consortium led by LASMO along with ENI and a group of five South Korean companies announced that it had discovered in the F1-NC174 well a large recoverable oil field called Elephant Field (also known as El Feel), with reserves around 700 MBB oil. In November 2000 a consortium led by REMSA along with TOTAL, OMV and SAGA announced the discovery of the NC186 oil field, which wildcat A1 flowed up to 2,500 B/D of a 41º API oil. In March 2001 they announces a second discovery by well B1-NC186, located 30 km east to the well A1, which produced up to 1,300 B/D of 40º API crude. Three new findings were made in 2005 in the prolific block NC186: the D1, I1 and J1 wells, initially flowing between 2,097 and 4,650 B/D of light oil. In January 2007 Woodside Energy (a consortium also participated by REMSA and Hellenic Petroleum) announced the finding of gas in their well C1-NC210, initially flowing 986 BOE/D. The well C1-NC210 is located about 150 km southwards the Al Wafa gas field. Actually oil fields are in production, although with a low production rate, but exploration remains stopped since 2011 does to safety problems.

Other paramount steps in the exploration history of the Murzuq basin were the findings by REMSA of the A1, B1, H1, M1, N1 and Q1 wells in NC115, and wells A1, B1, D1, J1 and I1 in block NC186, the AGIP wells, B1, C1 and F1 in block NC174, and the well D1 drilled by TOTAL in NC191.

1.1.2. Reserves and production:

After the BP Statistical Review of World Energy (June, 2014), the Libyan proved reserves at January, 1, 2014 were of 48.5 BBB of crude and 1.50 TCM of natural gas. The proved reserves of oil and natural gas remained unaltered respect to the beginning of 2007. Table 1 shows the evolution of oil and gas reserves in the last 20 years in Libya, North Africa and the whole of Africa.

Proved Reserves		***1992***	***2002***	***2013***
Oil (BBB)	*Libya*	22.9	36.0	48.5
	North Africa	37.2	52.2	66.5
	Africa	61.1	101.6	130.3
Natural Gas (TCM)	*Libya*	1.3	1.5	1.5
	North Africa	5.4	7.7	7.8
	Africa	9.9	13.8	14.2

Table 1.- Proved reserves of crude (in BBB) and gas (in TCM) for Libya, North Africa and the whole of Africa, and their evolution for the last twenty years. North Africa includes Algeria, Chad, Egypt, Libya and Tunisia. Values of reserves at the beginning of each year. Data from the BP Statistical Review of World Energy (June 2014).

According to these data, Libya results one of the African countries with larger oil in place reserves. Their crude proved reserves represent the 72.9% of the reserves of North Africa, and the 37.2% of the total reserves of Africa, as well as the 5.47% of the reserves of the OPEC and the 2.9% of the total proved reserves on the world. Respect to their reserves in natural gas, Libya has become an important gas province. Their current proved reserves of natural gas represent the 19.2% of the North African reserves, the 10.5% of the total reserves in Africa and the 0.8% of the gas reserves in the world.

Libya, as an OPEC member country, has their production submitted to quota. The last allocation was established in the OPEC meeting as 1.7 MMBED. The Libyan production in 2013 was 988 BBB of oil and 12.0 BCM of gas (BP Statistical Review of World Energy, June 2014). After a main drop in the production during 2011, these values represent the currently production tends to recover the activity before the production's drop occurred in 2011. Figure 2 shows the Libyan's evolution of crude and gas production during the last ten years.

The Libyan oil production during 2013 represents the 28.8% of the production in North Africa, the 11.2% of the total African production, the 2.7% of the oil produced by the OPEC and about the 1.1% of the world oil production. The production of natural gas smoothly arises during the period 2002-2007, with a trending to decrease after 2007 and a major drop during 2011 (see Fig. 2). During the year 2013 the Libyan natural gas production was of 12.0 BCM, which represents the 8.2% of the North Africa production, the 5.9% of the total Africa production and the 0.4% of the world production.

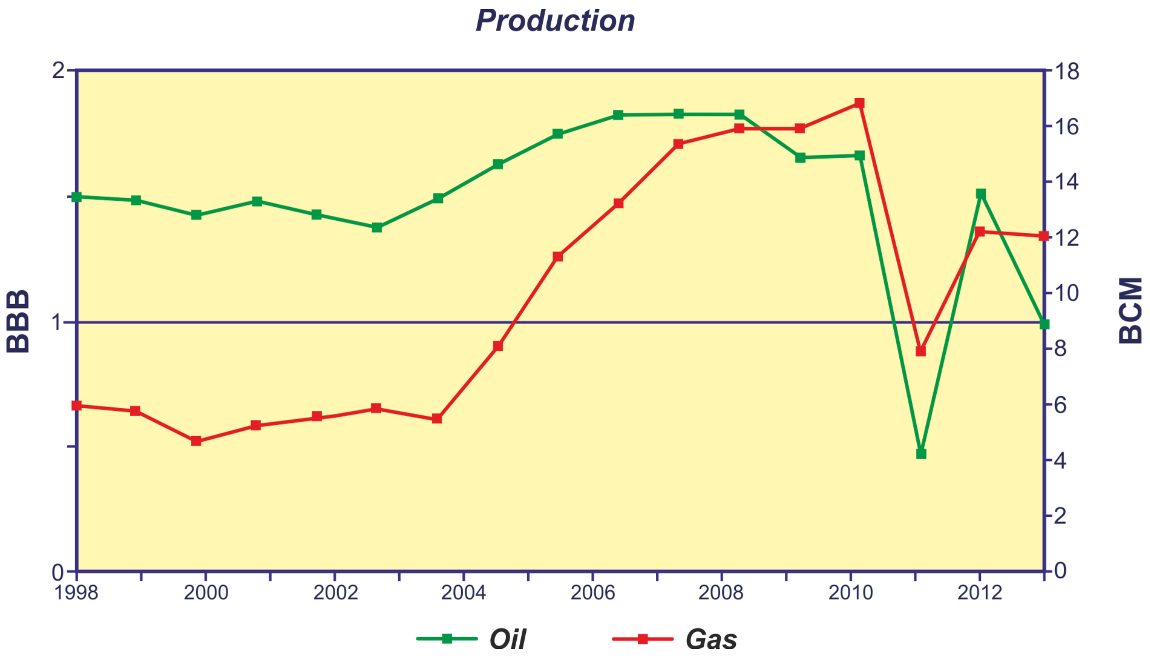


Figure 2.- Graph showing the evolution of oil and gas Libyan production since 1997 to 2013. Oil production in billion barrels (BBB axis), gas production in billions of cubic metres (BCM axis). Data from the BP Statistical Review of World Energy (June, 2014).

According with the above exposed data, the reserves-production ratio (R/P) for the wole Libya reach more than 100 years for both, oil and natural gas.

Oil and gas reserves and production in Libya are owing to the contribution of five main sedimentary basins (Fig. 1): Sirte Basin (onshore) and their offshore extension to the Pelagian (or Sabratah) Basin, the Ghadamis (or Hamra) Basin, which extents offshore to the Gulf of Gabes as the Musratah Basin, the Cyrenaica/Benghazi and the Murzuq Basins. Of these five basins, Sirte and their offshore extension Pelagian Basins hold by far the larger reserves and production rates of Libya, whereas Cyrenaica (Benghazi) and Murzuq Basins, still remaining lightly explored, constitute two promising productive areas.

The reserves of the Murzuq Basin represent about 7.4% of the Libya's reserves. The larger probed reserves in the Murzuq Basin are located in the NC115, NC174, NC186 and NC210 blocks. The last oil in place estimation for the Murzuq Basin is about 7.3 BBB of oil and about 1.0 TCM of gas.

The Murzuq Basin supplies about the 30% of the Libya's current oil production. The production of the Murzuq Basin began in late 1996, when the giant El Sharara Field comes onstream. Actually, El Sharara Fiel is producing about 200,000 B/D. Elephant Field started production by 2004, at an initial rate of 10,000 B/D rising to 125,000 B/D by 2007. Fields A and D in block NC186 started production in 2003-2004, producing in 2005 about 35,000 B/D.

1.2. METHODOLOGY:

The method used in this work is based in two mainstays: on the one hand, a bibliographic research and synthesis of the National Oil Corporation (NOC) reports collection, on the other hand, the direct observation and study of outcrops of the Paleozoic units exposed in the basin boundaries.

The Libyan NOC has collected, along the last decades, an important number of unpublished reports from the different oil companies operating in the area. The NOC allowed us the access to their archives, which resulted in a prolific and useful data base. The information provided by these bibliographic sources has been analysed, synthesised and updated, making it consistent with the field observations.

The Paleozoic stratigraphic units are located at subsurface in the Murzuq Basin, but they crop out in the tectonically uplifted zones which constituted the basin boundaries. The Gargaf, Atshan, Tihemboka and Tibesti Highs are these uplifted areas bounding the Murzuq Basin (Fig. 1) where more or less complete Paleozoic sequences can be observed. We had carried out a number of field campaigns to the Gargaf, Tihemboka and Tibesti zones in order to study directly the main features and characteristics of each stratigraphic unit and their hydrocarbon potential.

Finally, we will establish the relationships between the field observations and subsurface data.

1.3. OBJECTIVES OF THE THESIS:

The aim of this Thesis is to updating and synthesise the present-day knowledge on the Paleozoic Petroleum Systems of the Murzuq Basin mainly based in the above mentioned data base, which has been increased by other published papers and field observation of outcrops.

The work mainly focuses on the stratigraphy of the Paleozoic units which constitute the sedimentary fill of the Murzuq Basin, with special emphasis in those which constitute the Paleozoic petroleum systems. These stratigraphic units are present in the subsurface of the basin and, with different outcrops quality, in the basin boundaries as the Gargaf, Tihemboka and Tibesti Highs.

The main goals of the work are:

1. Description of the stratigraphic units including their boundaries, thickness distribution in the basin and lateral variations.

2. Biostratigraphic analysis and dating of these stratigraphic units.

3. Description of their sedimentary facies, facies associations and palaeoenviromental interpretation.

4. Sequence stratigraphic analysis.

5. Petrophysics and organic geochemistry evaluation.

6. To define the proved and/or the potential petroleum systems in the basin.

2. GEOLOGICAL SETTING

2.1. MESO-PROTEROZOIC TO LATE PALEOZOIC PALAEOGEOGRAPHIC EVOLUTION OF AFRICA.

During most of the Paleozoic, Africa was a part of the Gondwana supercontinent and the palaeogeographical evolution of the African Paleozoic basins was controlled, in broad, by the plate tectonic evolution of Gondwana and Pangaea until their fragmentation by rifting during Mesozoic times, whereas the evolution of the Tethys and the Mediterranean sea controlled the evolution of these basins (mainly the North African's basins) during late Mesozoic to Cainozoic times.

Based on different source data, Unrug (1996, 1997) has proposed a plate tectonic reconstruction from a time span covering from Meso-Proterozoic to late Paleozoic times. The evolutionary history includes the accretion of the former Rodinia supercontinent and their break-up, the subsequent accretion of terranes with the formation of the new Gondwana supercontinent and the assembly of Gondwana with the rest of the continental plates and formation of the Pangaea supercontinent. A synthesis of this plate tectonic evolution is showed in figure 3.

Rodinia (Fig. 3.A) was the ancestral supercontinent, which was formed during Meso-Proterozoic times (1600-1000 Ma) by the assemblage of a number of older Archean to Palaeo-Proterozoic cratons. At this time, the Congo, Kalahari and West Africa cratons already exist, but whereas the former Congo and Kalahari cratons occupied the western part of Rodinia, the West Africa Craton was located at their eastern part (see figure 3.A).

At the early Neo-Proterozoic Rodinia began to break-apart (Fig. 3.B). In this time, the West Africa Craton remained still separated from the Congo and Kalahari cratons. The eastern terranes of Rodinia, including the West Africa Craton, moved eastwards at the time that they rotated in an anticlockwise direction, whereas the western terranes, including the Congo and Kalahari cratons, drifted westwards and suffers a clockwise rotation. Younger terranes that latter will form the Eastern Sahara and the Arabia Shield were formed at this time as an oceanic microplate and a magmatic arc respectively in the Arabian-Nubian Ocean.

The rotated and moved round cratons were assembled during late Neo-Proterozoic times in a new configuration know as the Pannotia supercontinent. The borders of the former cratons were intensively deformed by the so called Pan-African orogeny. In this time, the future Africa already was constituted by a set of six cratons of diverse age and origin. The Pannotia Supercontinent had a relatively brief existence, and during the earliest Paleozoic it broke apart

Legend:

- 🟨 *Cratons*
- ▨ *Meso - Proterozoic mobile belts*
- 🟩 *Late Proterozoic mobile belts*
- 🟦 *Oceans*
- ☐ *Continents*
- ↕ *Break-apart axis*
- ⇌ *Shear zone*
- → *Direction of plate movement*

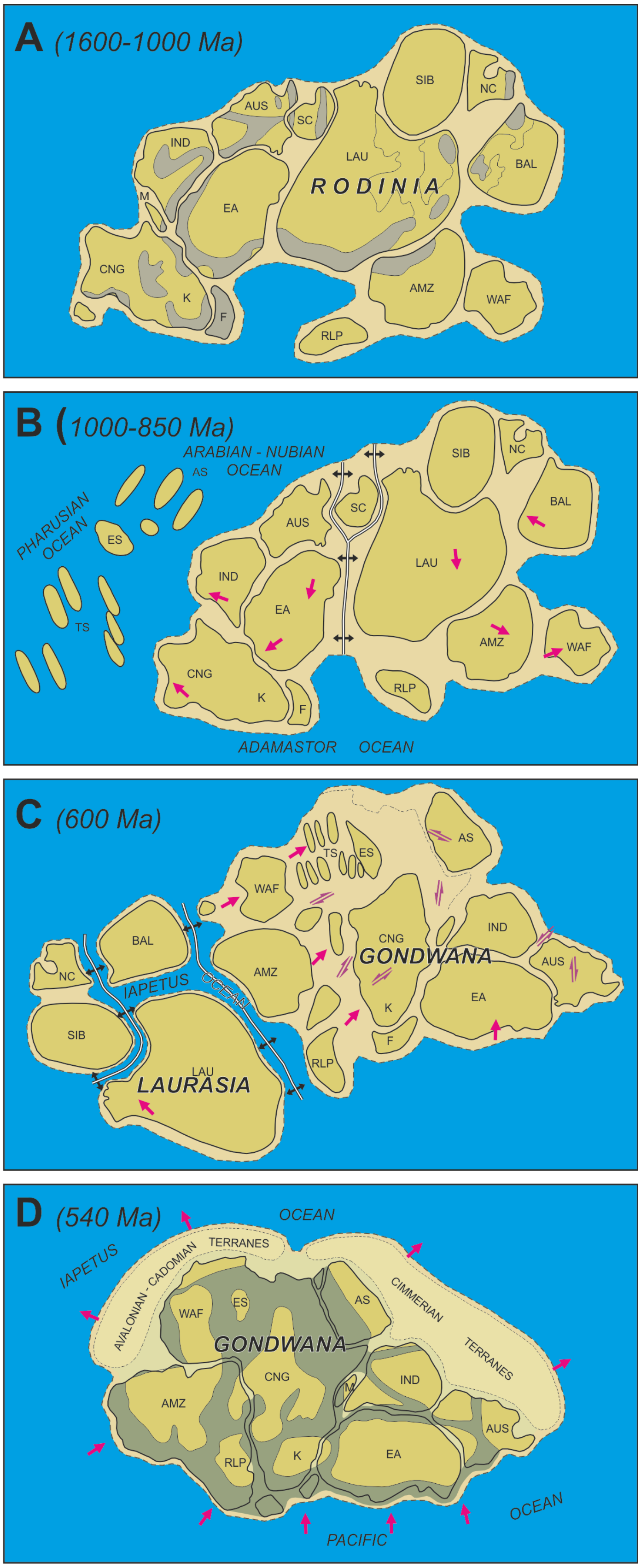


Figure 3.- Palaeogeographical plate tectonic reconstruction from Rodinia to Gondwana. **A)** Reconstruction of Rodinia during Meso-Proterozoic (ca 1600 - 1000 Ma). **B)** Break-up of Rodinia during early Neo-Proterozoic (ca 1000 - 850 Ma). **C)** Reconstruction of Panottia supercontinent and the Pan-African orogeny during the late Neo-Proterozoic (ca 600 Ma). **D)** Reconstruction of the Gondwana assembly at the latest Neo-Proterozoic – early Palaeozoic (ca 540 Ma). All the figures are redrawn **from Hallet (2002).** Key: **AMZ** = Amazonian. **AS** = Arabian Shield. **AUS =** Australia. **BAL** = Baltica. **CNG** = Congo - Nile. **EA** = East Antarctica. **ES** = East Sahara. **F** = Falkland. **IND** = India. **K** = Kalahari. **LAU** = Laurentia – North America. **M** = Madagascar. **NC** = North China. **RLP** = Río de la Plata. **SC** = South China. **SIB** = Siberia. **TS** = Touareg Shield. **WAF** = West Africa.

along the line of the Neo-Proterozoic suture forming the Iapetus Ocean (Fig. 3.C). Laurentia, Baltica, Siberia and North China were separated from the rest and formed Laurasia, whereas the assemblage comprising Africa, Antarctica, South America, Australia and India remained assembled forming the Gondwana supercontinent. Gondwana and Laurasia will follow each separated history for the next 300 Ma.

At the latest Neo-Proterozoic – early Paleozoic (c.a. 540 Ma) Gondwana exists already as the fused cratons which previously formed the eastern Pannotia (Fig. 3.D). The assembly of Gondwana was followed by post-orogenic magmatism and crustal thickening accompanied by uplift, rifting and erosion. There exist a number of works gathering the present status of the knowledge of the Late Proterozoic - Early Phanerozoic evolution of Gondwana (Trompete, 1994; Storey et al., 1996; Pankhurst and Rapela, 1998; Yoshida et al., 2003). All of these works considered that the southern margin of Gondwana was an active convergent margin, with subduction and tectonic deformation, whereas the northern margin was a wide passive margin bordered by a broad and shallow shelf where thick successions of shallow marine to non-marine sediments were accumulated. During Ordovician times, the northern margin of Gondwana becomes unstable, and fragments of continental crust including Neo-Proterozoic rocks, as Avalonian, Cadomian and Cimmerian terranes break up and drifted northwards (Matte, 2001), and collided with Laurentia, Baltica and Siberia plates respectively, resulting in the Caledonian orogeny, which did not directly affect Gondwana.

The Iapetus Ocean, originated by the rupture of Pannotia, reached their maximum extent during the late Cambrian-early Ordovician times (Harlan and Gayer, 1972), when North Africa, as a part of western Gondwana, occupied a high-latitude position, close to the South Pole (Fig. 4.A). Thereafter, the Iapetus Ocean separating Gondwana from Laurentia progressively closed as Gondwana drifted northwards, to lower latitudes (Van Houten and Hargraves, 1987) and a spreading axis produced the birth of a new ocean: the Rheic Ocean (Bozkurt et al., 2008) (Fig. 4.B).

The northwestern margin of Gondwana starts to collide with Laurasia during the Middle-Upper Devonian, but deformation lasted up to Carboniferous times, when a fold-belt with their associated foreland basins developed, mainly in Morocco and Algeria (Figs. 4.C and D). By the early Permian, the collision between Gondwana and Laurasia resulted in a new supercontinent called Pangaea, which included the whole of the continental plates (Fig. 5). The suture zone between northwestern Gondwana and Laurasia was a major shear-zone with strike-slip dextral component.

The Pangaea supercontinent was surrounded by a world wide ocean called Panthalasa. Along the line of the shear-zone, a major oceanic gulf was formed, separating the older northern Gondwana from Laurasia. This large

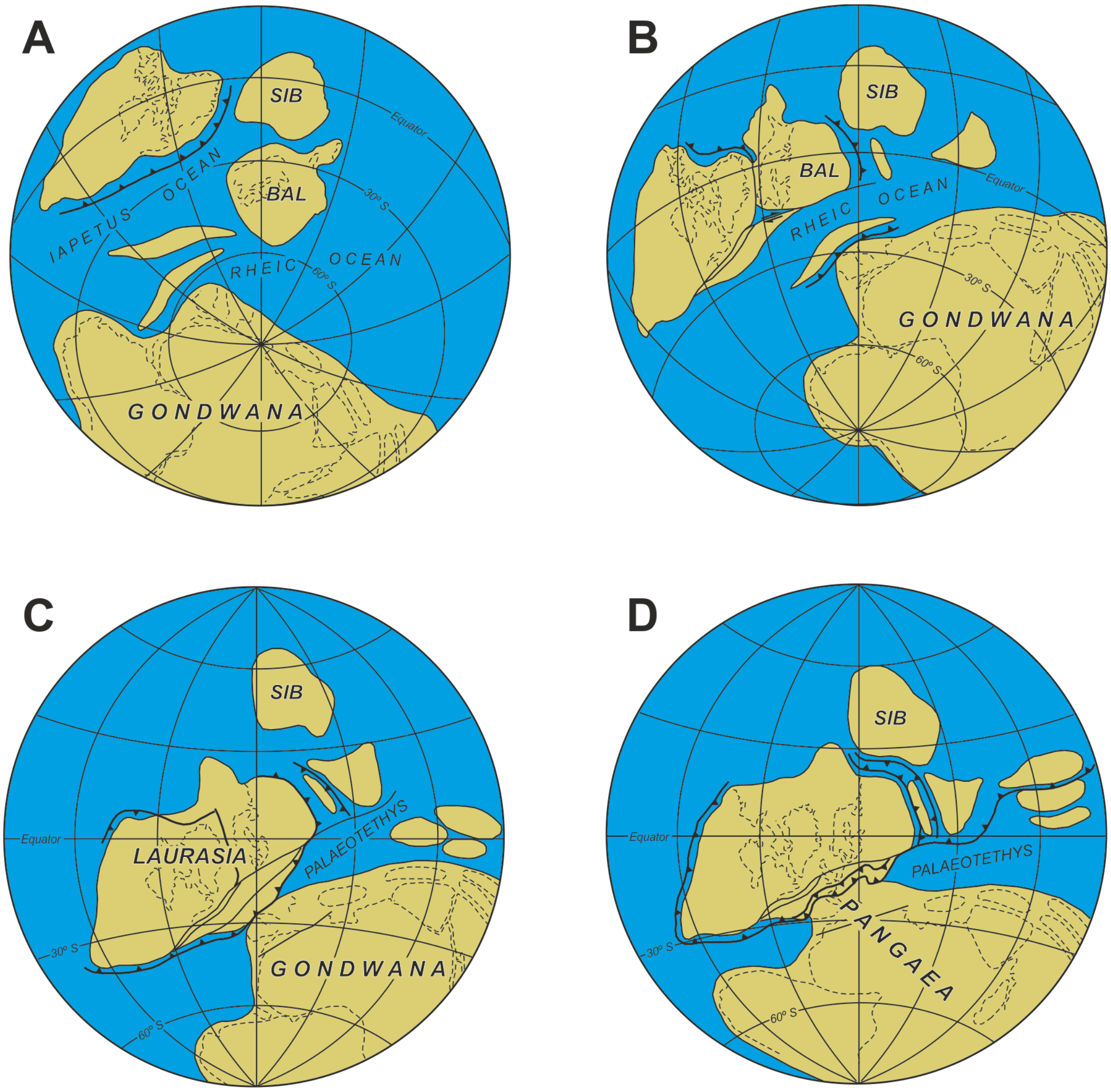


Figure 4.- Palaeozoic plate tectonic evolution from Middle Ordovician to Lower Carboniferous. **A** = Middle Ordovician (465 Ma). **B** = Middle Silurian (425 Ma). **C** = Middle Devonian (375 Ma). **D** = Early Carboniferous (340 Ma). Redraw from Matte (2001).

embayment was the precursor of the Tethys Ocean, and resulted by creation of new oceanic crust from a spreading wedge developed parallel and close to the northern margin of Gondwana. The new-generated oceanic crust subduced under the South Asia and Siberia continental plates (Fig. 5).

The break-up of Pangaea began during the late Triassic, with development of intracratonic rift grabens. One of these separated the former East and West Gondwana terranes, producing the opening of the South Atlantic Ocean. Other major rift graben was produced following approximately the older suture zone between Laurasia and Gondwana, giving rise to the formation of the Palaeotethys Ocean. The development of spreading axis in the Tethys region is recorded in North Africa by associated igneous rocks, faults and several unconformities within the Triassic sequences.

The Tethys Ocean had a complex history, and their evolution give rise to the Mediterranean Sea (Decourt et al., 1986; 1993; Ricou, 1994). The oldest oceanic crust recognized in the Tethys region is Middle Jurassic in age, and corresponds with the present-day western Mediterranean area. By the Upper Jurassic times, the former Laurasia and Gondwana were already separated by the Tethys Ocean, generated along the older line of the Pangaea suture.

By the early Cretaceous times, western Tethys was a narrow and relatively young ocean developed along the above mentioned spreading axis, whereas the eastern Tethys was a wider and older ocean bounded southwards by a spreading axis rimmed to the continental plate, and northwards by a subduction zone of oceanic crust under the Euro-Asia plate. In this situation, Africa rotated in a clockwise sense and moved eastwards respect to Euro-Asia. This plate movement produced stretching and crustal thinning, which was responsible of a generalized Cretaceous marine transgression in North Africa. According to Anketell (1996), the Cretaceous sedimentation in Sirte Basin (North of Libya) was controlled by a set of horsts and grabens northwest-southeast oriented.

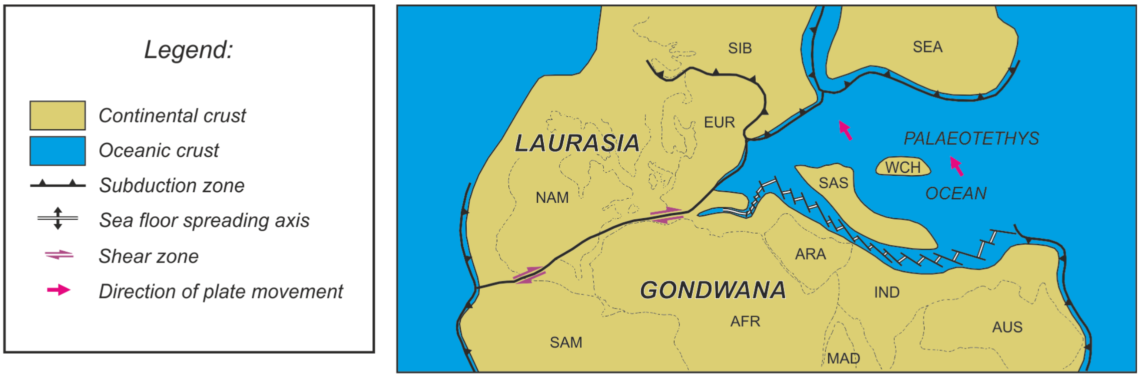


Figure 5.- Plate tectonic reconstruction of the Pangaea supercontinent during early Permian. Redraw from Hallet (2002). Key: **AFR** = Africa. **ARA** = Arabian Shield. **AUS** = Australia. **EUR** = Europe. **IND** = Great India. **MAD** = Madagascar. **NAM** = North America. **SAM** = South America.**SAS** = South Asia. **SEA** = South-east Asia. **SIB** = Siberia. **WCH** = West China.

At the end of the Upper Cretaceous the seafloor spreading in western Tethys finished and the motion of Africa respect to Europe changed to a north or northeast direction; the Tethys begun to close, giving rise to the formation of the closed Mediterranean sea. The compression produced by the Africa and Europe approach produced the Alpine orogenic cycle.

2.2. THE GEOLOGY OF NORTH AFRICA: CRATONS AND MOBILE BELTS:

In broad, the Geology of Africa can be summarized as formed by cratons and mobile belts (Petters, 1991). The cratons are areas non-deformed since Early to Middle Proterozoic times. They include shields - made of basement complexes - and platforms - made of a basement covered by a younger sedimentary cover (Fig. 6).

The oldest orogeny documented in Africa is located in the Limpopo province, in the Kalahari craton, where the outcropping high grade metamorphic rocs have been dated by Cahen et al. (1984) as c.a. 3.8 Ga. old (Archaean). There are other late Archaean major orogenic cycles as the Leonian and the Liberian orogenies (c.a. 2.9 and 2.75 Ga. old respectively). The Early Proterozoic Eburnean orogeny (2.27 to 2.0 Ga.) affected nearly the whole of Africa, whereas the Meso Proterozoic Greenvilian orogeny (1.4 to 1.1 Ga.) seems to be recorded only south of the Equator. The most ubiquitous and widely recognized orogeny corresponds with the Late Proterozoic to Early Paleozoic Pan-African orogeny, which affected the entire continent except the cratons and can be related to the assembly of Gondwana by closing of the Mozabique and Adamastor Oceans (Trompete, 1994; Pissarevsky, 2005; Pissarevsky et al., 2008).

The African cratons are constituted by rocks displaying a wide range of ages (Fig. 6). The older ones are the Zaire, Kalahari and West African cratons, which are made of Archaean to Early Proterozoic rocks, whereas in the Bangweulu block, located in Central Africa and containing a part of the Kibaran and Ubendian belts, only Early Proterozoic rocks have been recognized.

The Sahara Platform (Figs. 6 and 7), also called the North African Platform is a platform (that is, part of a craton covered by a younger sedimentary cover) occupying most of Northern Africa. Their basement is partially constituted by the Pan-African Pharusian belt towards the western, and by the East Saharan Craton in their eastern part. The East Saharan Craton crops out in the Uweinat zone, forming an inlier of rocks dated by Cahen et al. (1984) up to 2.67 Ga. old. The sedimentary cover of the North African Platform consists of a thick sequence of Phanerozoic rocks which includes the main Paleozoic intracratonic basins in North Africa, which are covered, in turn, by younger Mesozoic and Cainozoic sequences.

The main Paleozoic sedimentary basins located onshore the Sahara Platform are (Fig. 7), from west to east: the Essaouira, Doukkala and Rarb Basins in the western Moroccan margin; Tindouf and Bechar Basins between Mo-

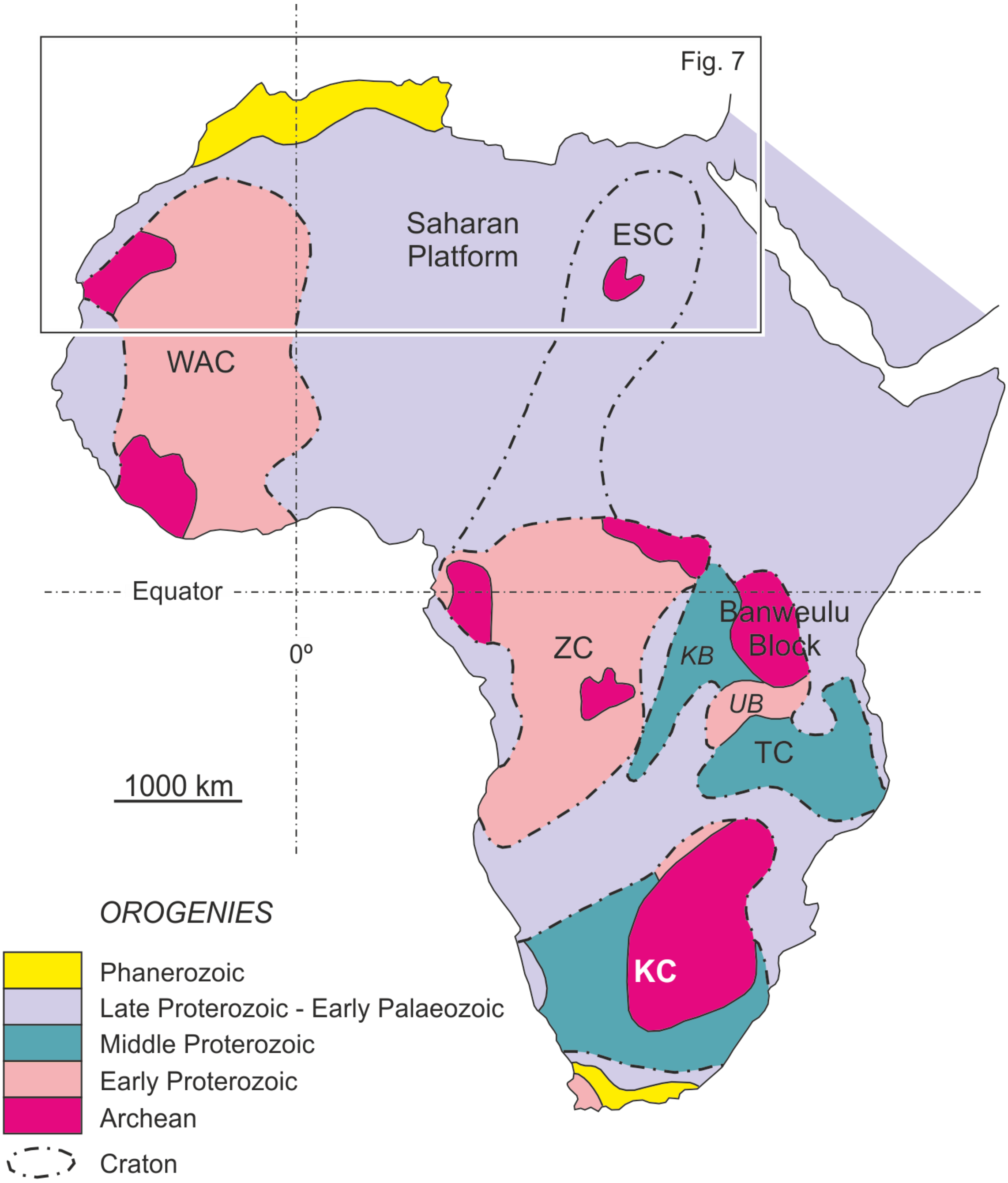


Figure 6.- Geological sketch of Africa showing the location of cratons and mobile belts. Key: **WAC** = West African Craton; **ESC** = East Saharan Craton; **ZC** = Zaire Craton; **TC** = Tanzania Craton; **KC** = Kalahari Craton. **KB** = Kibaran Belt; **UB** = Ubendian Belt. Box indicates the area represented in figure 7. Redraw from Petters (1991).

rocco and Algeria; Reggane, Gourara, Ahnet, Oued Mya, and Illizi Basins in Algeria; Ghadamis and Hamra Basins partially between Algeria, Tunisia and Libya; Murzuq, Sirte and Kufrah Basins in Libya and the Abu Gharadig Basin in north Egypt (see figure 7). These sedimentary basins are bounded by tectonic uplifts allowing that Paleozoic successions locally crop out.

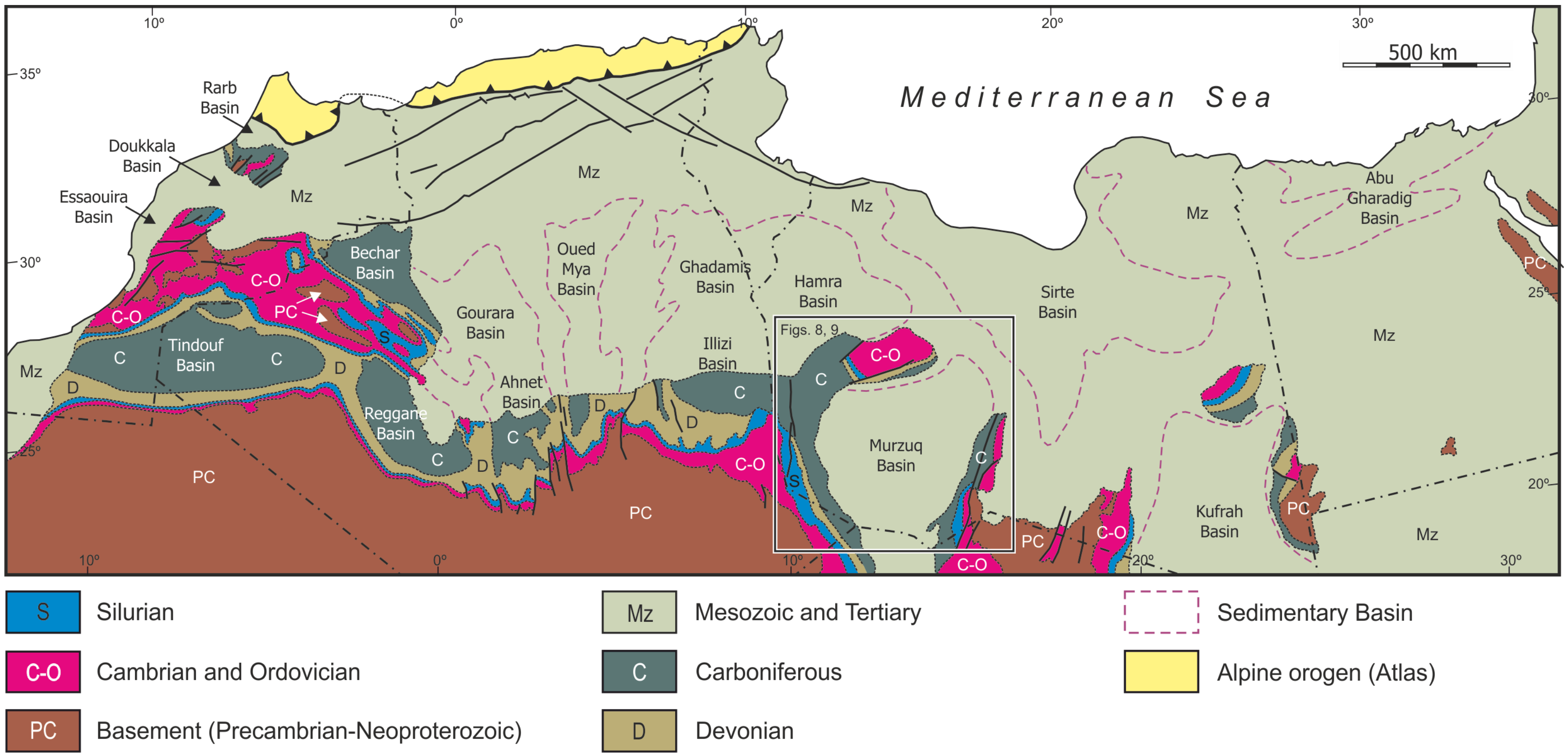


Figure 7.- Palaeozoic outcrops and major sedimentary basins in North African Sahara Platform. See location in figure 6. The inset shows the Murzuq basin represented in figures 8 and 9. Redraw from Boote et al. (1998).

The Murzuq basin (Figs. 7 and 8), which constitutes the objective of this study, is bounded by the following tectonic uplifts: The Atshan Arch and the Gargaf High to the north, the Tihemboka High to the southwest and the Tibesti High to the southeast (Fig. 8), whose tectonic evolution will be described later.

2.3. THE MURZUQ BASIN:

A preliminary framework of the Murzuq Basin was firstly established by the geological map published by Desio (1939). The Murzuq Basin (Fig. 8) is an elliptical in shape, 800x800 km large, covering an area of over 350,000 km^2. It is a large intracratonic sag basin located in the North African Platform, which occupies a part of the southwest Libya and extends southwards into Niger, where it is there known as the Djado Basin. In their depocenter it reach more than 11,000 feets (3700 m) in depth (Fig. 8).

It is not a sedimentary basin in the normally accepted sense, but it could more accurately be described as an erosional remnant of a much larger Paleozoic and Mesozoic continental margin which originally extended over much of North Africa (Davidson et al., 2000), so, the present-day basin geometry bears

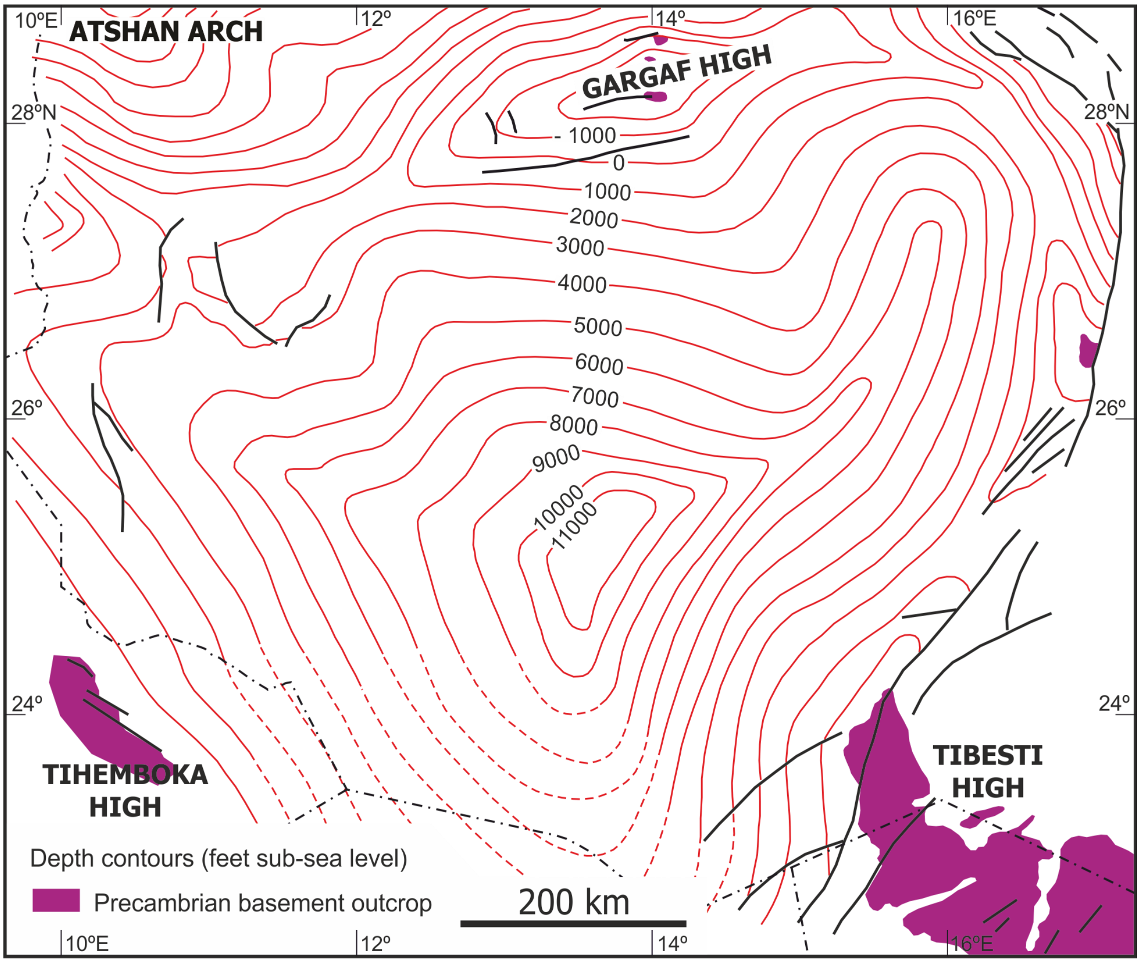


Figure 8.- Contour map of the basement of the Murzuq Basin (in feets). The contour curve = corresponds with the sea-level. Contour interval 1000 fts.

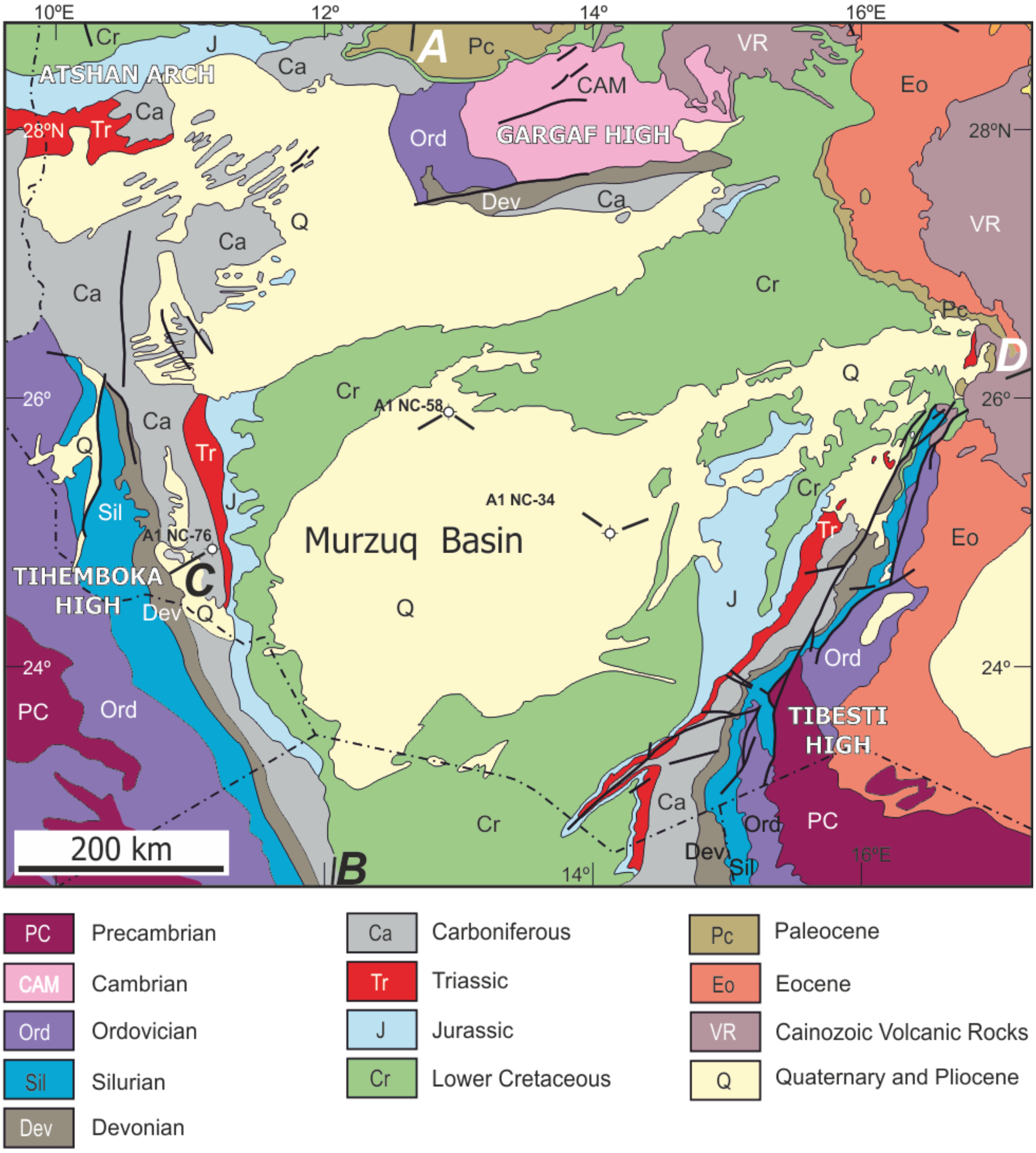


Figure 9.- Geological map of the Murzuq basin and its boundaries showing the location of the REMSA permits and wells cited in this work. See location in figure 7. A-B and C-D = cross sections showed in figure 10.

little relation to the broader and larger North African sedimentary basin which existed in the area during the Paleozoic times. The present-day borders of the basin are defined by erosion resulting from multiphase tectonic uplifts. The flanks comprise (Figs. 8, 9): the Tihemboka high to the SW, the Tibesti high to the SE, and the Gargaf and Atshan highs to the N and NW respectively. These uplifts were generated by various tectonic events ranging from Middle Paleo-

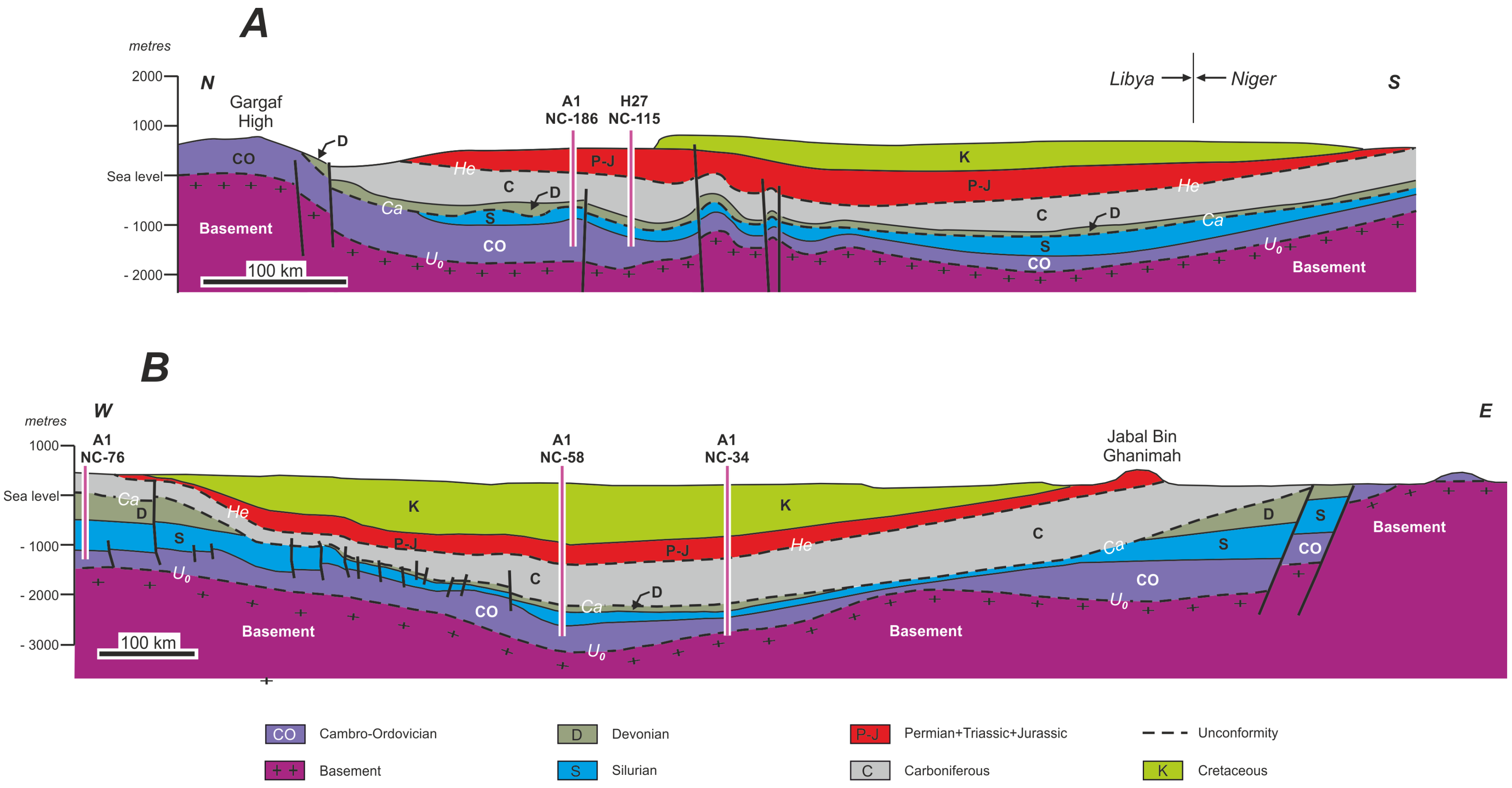


Figure 10.- N-S (A) and E-W (B) geological cross sections of the Murzuq Basin. See location in figure 9.

zoic to Tertiary in age, but the main periods of uplift took place during Middle Cretaceous (Austrian) to Early Tertiary (Alpine) orogenic cycles. There is little evidence of tectonic control on sedimentation during Paleozoic times; the main tectonic influence on sedimentation at Paleozoic times was probably exerted across the NE part of the present-day basin, causing a progressive thinning of the Silurian deposits towards the NE.

The basin is filled by a thick sedimentary sequence predominantly made of Paleozoic marine sediments and non-marine Mesozoic deposits (Fig. 10). The Paleozoic sequence was deposited over a neo Proterozoic to Precambrian basement. Several generations of structuring, mainly compressional and transpressional in nature, are recognized within the basin, but the cumulative structural deformation is relatively minor. Fault arrangement displays considerably variations, although the N-S trend is dominant.

In the central part of the basin the sedimentary infill reach more than 3000 metres in thickness (Fig. 10). Davidson et al. (2000) point out that despite erosive episodes during several phases of uplift and erosion throughout the history of the basin, the maximum sedimentary thickness probably never exceeded 5000 metres at any single point in time.

The basement of the basin is constituted by two assemblages bounded by an unconformity. The first one is constituted by a set of high-grade metamorphic rocks as mica-schists, gneisses and amphibolites, associated with plutonic rocks (granite and granodiorite). The second association is constituted by low-grade metamorphic to unmetamorphic rocks of Precambrian age named Mourizidie Formation after Jacqué (1962). Both assemblages are cut by the Pan African unconformity, Precambrian to early Paleozoic in age, forming a non-conformity which is considered the basal unconformity (U_0 in Fig. 10) of the basin. Other major basin-scale unconformities recognized within the sedimentary record of the basin are the Caledonian and Hercynian unconformities (Ca and He respectively in Fig. 10).

2.3.1. Structural evolution of the Murzuq Basin:

According to Klitzsch (2000), the Lower Paleozoic sedimentation in North Africa was controlled by a system of horsts and grabens, striking NNW-SSE to N-S, which developed during Cambrian to early Ordovician times. Coward and Ries (2003) suggest that these horsts and grabens could be related with the former shear zones originated by the indentation of the rigid West African Craton with the Pan-African nucleus of Northeaster Africa.

These structural relief formed large and elongated subsiding troughs or basinal areas where Upper Precambrian to Cambrian molasse were accumulated. These were the precursor of the Palaeozoic basins and during the periods of high sea level, become the routes for long-distance marine transgressions to the South or Southeast over a part of Africa. Tectonic subsidence of these structurally low areas lead to the accumulation of relatively thick sequences of Palaeozoic marine sequences during highstand, whereas during periods of lowstand and marine regression, these areas were filled by transitional to continental sediments. The intervening uplifted horsts were areas sub-

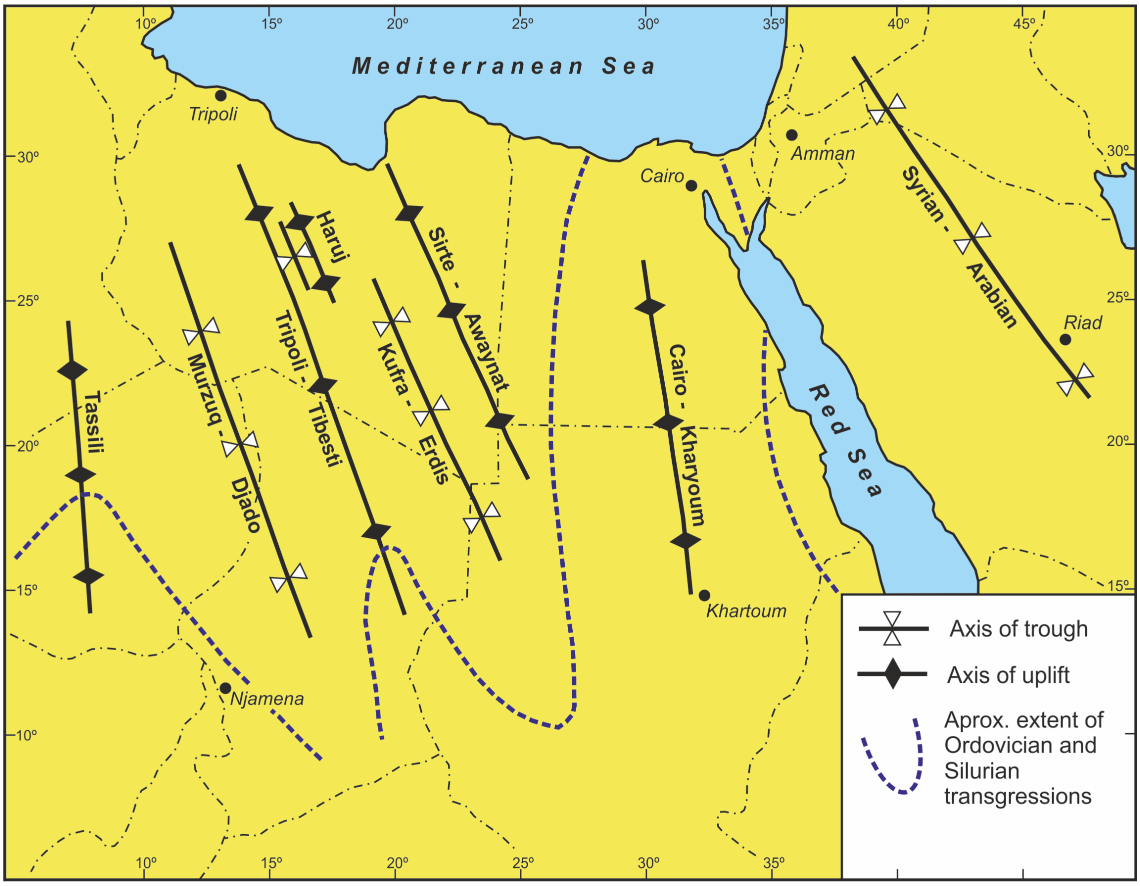


Figure 11.- Structural pre-Palaeozoic relief of NE Africa controlling the deposition of Cambrian to Carboniferous sequences. Redraw from Klitzsch (2000).

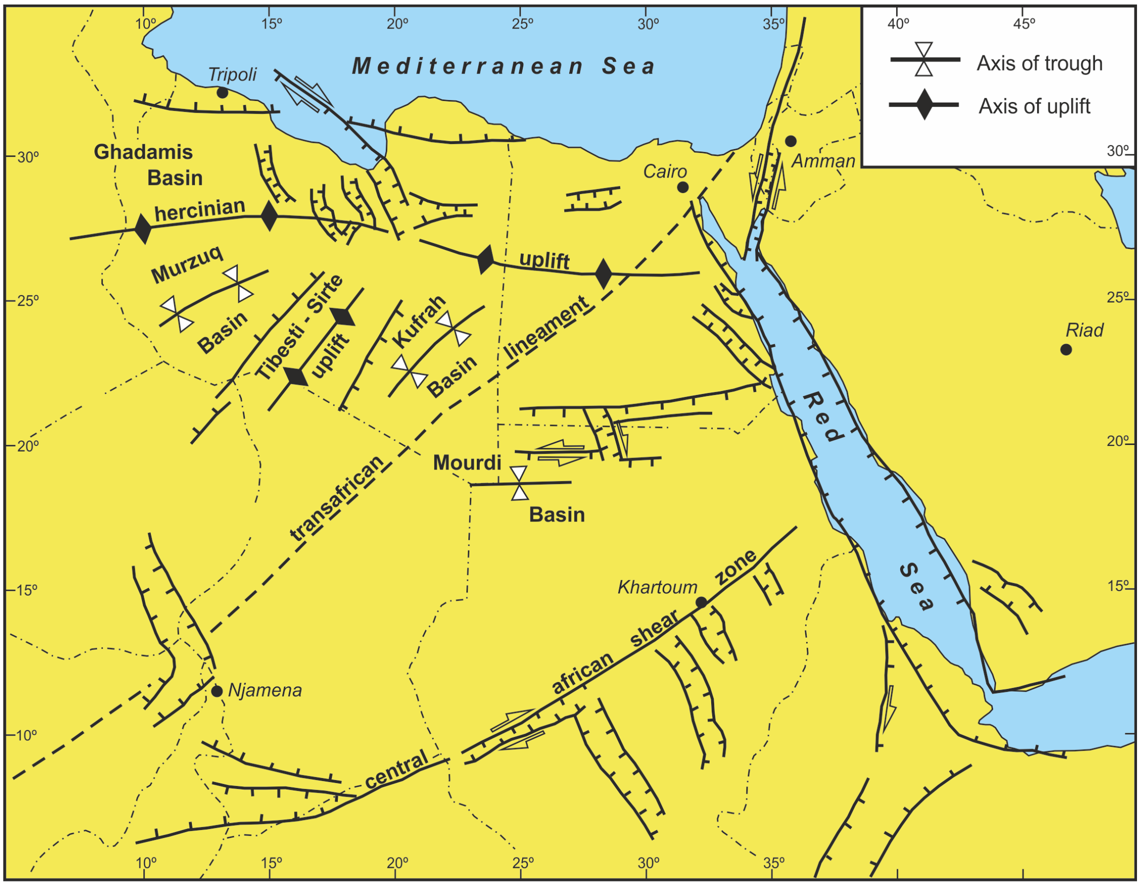


Figure 12.- Main structural elements developed in NE Africa after Hercynian orogeny. Redraw from Klitzsch (2000).

ject to reduced sedimentation and/or erosion. Figure 11 shows a schematic reconstruction of this tectonic relief in NE Africa.

This horsts and grabens structuration produced important and rapid thickness variations in the Cambrian and Ordovician sequences. So, the thickness distribution of the Ordovician deposits ranges from more than 2500 metres in some zones of the Anti-Atlas (Morocco) to almost 0 metres in some of the intervening grabens. Klitzsch (2000) documented an early Paleozoic horst cropping out at Mouridie, in the SE border of the present-day Murzuq Basin. In this area, lower Silurian shales overlie a basement of Proterozoic rocks which, in turn, is locally covered by a few metres thick sequence of Ordovician sandstones, while towards WSW and ENE of this area, several hundred-metres of pre-Ordovician strata are present on the downthrown sides of NNW striking normal faults. This horst can be traced as a gravity anomaly through Chad and Libya, and northwards became in the called Tripoli-Tibesti uplift (Fig. 11). The Tripoli-Tibesti and the Tassili are two uplifts striking NNW-SSE and N-S respectively, which constituted the East and West boundaries of the Murzuq-Djado trough (see Fig. 11).

Seismic evidence shows as the Cambro-Ordovician succession accumulated in graben structures were submitted to extensional faulting, but these intrabasinal faults are widely spaced and lead relatively small displacement, usually less than 100 metres, and frequently, they display a subseismic range. In any case, the cumulative structural deformation produced by this extensional fault system in the sedimentary record of the basin is considered as relatively minor.

The collision of Gondwana and Laurasia plates at the late Paleozoic times gives rise to the Hercynian orogeny, which in North Africa resulted in the folding of the Anti-Atlas region (Morocco) and the uplift and partial erosion of large areas - bounded by an East-West trending fault system - of Algeria, Tunisia, Libya and Egypt. As a consequence, the older Cambrian-Ordovician North -South striking structural relief was overprinted by these East-West oriented structural uplifts. In Libya, this E-W Hercynian uplift was the forerunner of the Atshan and Gargaf archs, and compartmentalized the former Murzuq-Djado trough into the Murzuq Basin (southwards) and the Ghadamis Basin to the North (Fig. 12). Eastwards, this Hercynian uplift resulted in the erosion of the Paleozoic rocks in large areas of Sirte Basin and Egypt.

The uplift of these large areas in North Africa striking E-W was accompanied, somewhat latter, by faulting and rifting along the present-day Mediterranean and the Egyptian-Sudanese border towards southern Libya. In the eastern Sirte Basin, continental Permotriassic rift-basins developed (Fig. 12), and southwards of the large, east-west oriented uplifted zone in north Libya and Egypt, continental sedimentation filled the Murzuq and Kufrah Basins.

2.3.2. Sedimentary record of the Murzuq Basin:

The sedimentary infill of the Murzuq Basin comprises rocks from Cambrian to Eocene ages; however, the major and thicker sedimentary record corresponds to the relatively continuous Palaeozoic succession, whereas the Mesozoic and Cenozoic deposits are limited to thin and discontinuous sequences. The figure 13 is a stratigraphic chart showing the sedimentary infill of the Murzuq Basin and their stratigraphic breaks. The sedimentary infill of the Murzuq Basin unconformably overlies a Precambrian basement composed of high-grade metamorphic rocks associated with plutonic rocks, as well as low-grade to unmetamorphic rocks, Precambrian in age, known as the Mourizide Fm. Both, the plutonic and metamorphic rocks are cut by the Pan-African unconformity which constitutes the basal unconformity of the Basin (U_0 in Fig. 10).

Classically, the sedimentary record of the Murzuq Basin has been divided into four major sedimentary sequences: 1) Cambrian to Ordovician; 2) Silurian; 3) Devonian to Carboniferous, and 4) Mesozoic.

The Cambrian to Ordovician sequence, which unconformably overlies the Precambrian basement, matches up with the Lower Palaeozoic Gargaf Group, a detrital unit constituted by five formations named, from bottom to top: Hasawnah, Ash Shabiyat, Hawaz, Melaz-Shuqran and Mamuniyat. All of these formations are detrital, and bounded by uncorformities of different nature except for the boundary between the Ash Shabiyat and Hawaz formations, which is a non -erosive concordant surface.

The Silurian sequence is a fine- to medium-grained detrital sequence that overlies a complex erosive surface resulting from the Late Ordovician glaciation. It constitutes a relatively continuous sequence wich includes a transgressive and high sea level episode followed by a regressive progradation. The lower transgressive and high sea-level deposits are made by the Bir Tlacsin and Tanezuft formations, the last one includes the Hot Shale Member. The upper regressive deposits correspond with the Akakus Formation. The Silurian sequence is a ubiquitous one which can be recognized with similar characteristics across North Africa, from Morocco to the West to Arabia to the East (Lüning et al., 2000; 2005; Eschard et al., 2005).

The Devonian-Carboniferous sequence unconformably overlies the terminal Silurian Caledonian unconformity. It represents the continuous marine deposition locally punctuated by local unconformities that in some cases are the responsible of major thickness variations. Their deposits are both, detrital and carbonate, and include the Tadrart, Quan Kasa, Awaynat Wanin, Marar, Assedjefar, Dembaba and Tiguentourine formations, the last one is non-marine in origin. The sequence is capped by the Late Carboniferous Hercynian unconformity.

The Mesozoic sequence, which is not the objective of this study, is absent in the uplifts bordering the Murzuq Basin (Tihemboka, Tibesti, Gargaf and Atshan highs), and only a partial succession is present in the central part of the basin (see Figs. 9, 10). The most complete Mesozoic sequence crops out southwards of the basin, in the SE and SW borders, near of the Tihemboka and Tibesti highs, and it has been drilled in subsurface only in the southern

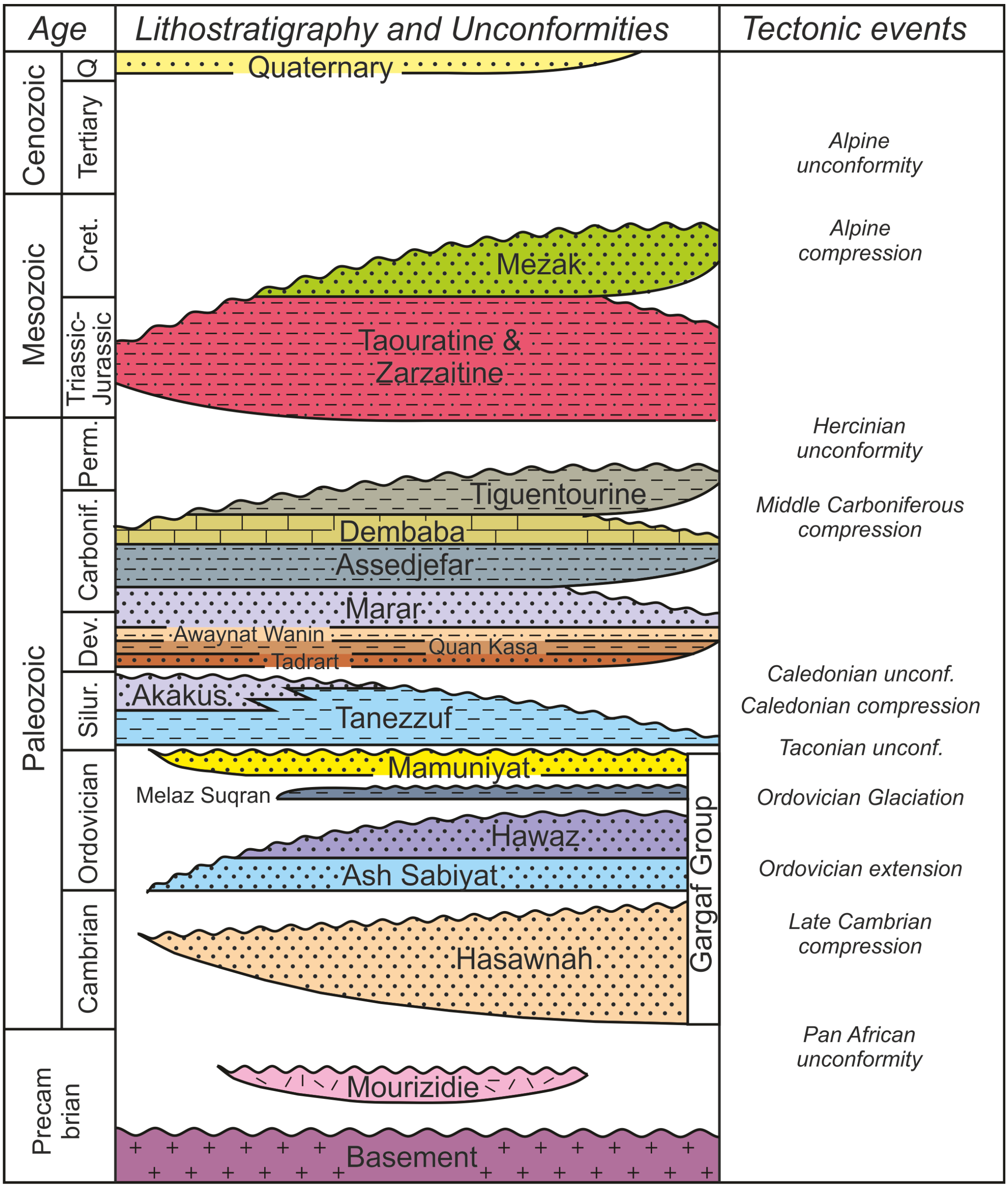


Figure 13.- Stratigraphic chart for the sedimentary infill and the main tectonic events recorded in the Murzuq basin. After Marzo and Ramos (2003).

half of the basin. Towards the North, the Mesozoic sequence is only represented by Cretaceous rocks, which occupy larger extensions of the basin. The Mesozoic sequence is made by continental detrital sediments and includes the Triassic Zarzaitine Fm, the Jurassic Touaratine Fm. and the Cretaceous Mezak Fm.

In general, sedimentation rate was low in the Murzuq Basin and the sedimentary infill in the depocenter reach about 3000 metres in thickness.

3. PALAEOZOIC STRATIGRAPHY

3.1. PALAEOZOIC SIGNATURES IN THE MURZUQ BASIN:

The Palaeozoic sedimentary infill of the Murzuq Basin records a set of major basin-scale unconformities which reflect the orogenic history of the area and/or other major geological processes occurred in the basin and, in turn, controlled deposition. These basin-scale unconformities allow us the stratigraphic subdivision of the Palaeozoic sedimentary record in a number of sequences. The main basin-scale unconformities are the Pan-African, Taconian, Caledonian and Hercynian unconformities. Other major events controlling deposition in Murzuq during Palaeozoic times were the Early Ordovician extension and the Late Ordovician glaciation. All these geological processes left their fingerprints on the sedimentary infill of the basin and are marked in the stratigraphic chart (Fig. 13). Other unconformities which could be recognized within the sedimentary record are minor or belong to the younger Austrian and Alpine cycles, and consequently, they don't affect the deposition of the Palaeozoic sequences.

The Pan-African orogeny:

The Pan-African orogeny is related to the collision and welding of a set of plates which resulted in the formation of the Panottian supercontinent (see Fig. 3.C). It is an orogenic event extensively represented across Africa that occurred during the Late Proterozoic to Early Cambrian times, covering a time span from 600 to 550 Ma (Cahen et al., 1984). It involves schists Late Proterozoic in age and intrusive granites usually older than Late Cambrian, although locally younger granitic rocks have been dated as 495 Ma (Early Ordovician) or even 418 Ma (Silurian), suggesting that intrusive activity continued after the end of the Pan-African orogeny, when the Middle Cambrian cratonisation was effectively concluded. The Pan-African orogeny is related with the basal unconformity of most of the sedimentary basins in North Africa, separating a basement of the Paleozoic sedimentary infill. In the Murzuq Basin we notated this surface as U_0 (Fig. 10).

The Pan-African basement of the Murzuq Basin is constituted by two assemblages bounded by an unconformity: a) crystalline (granite and granodiorite) rocks, Palaeoproterozoic (early Precambrian) in age associated with high-grade metamorphic rocks (mica-schists, gneisses and amphibolites), both belonging to the Eastern Saharan craton, which are unconformably overlied by, b) a metasedimentary sequence, Mesoproterozoic to early Cambrian in age, known as the Mourizide Fm. This formation crops out in the Mourizide high, in the SE border of the Murzuq Basin, where it was defined by Jacqué (1962). The Mourizide Fm constituted a 50 to 300 m thick detrital succession made up

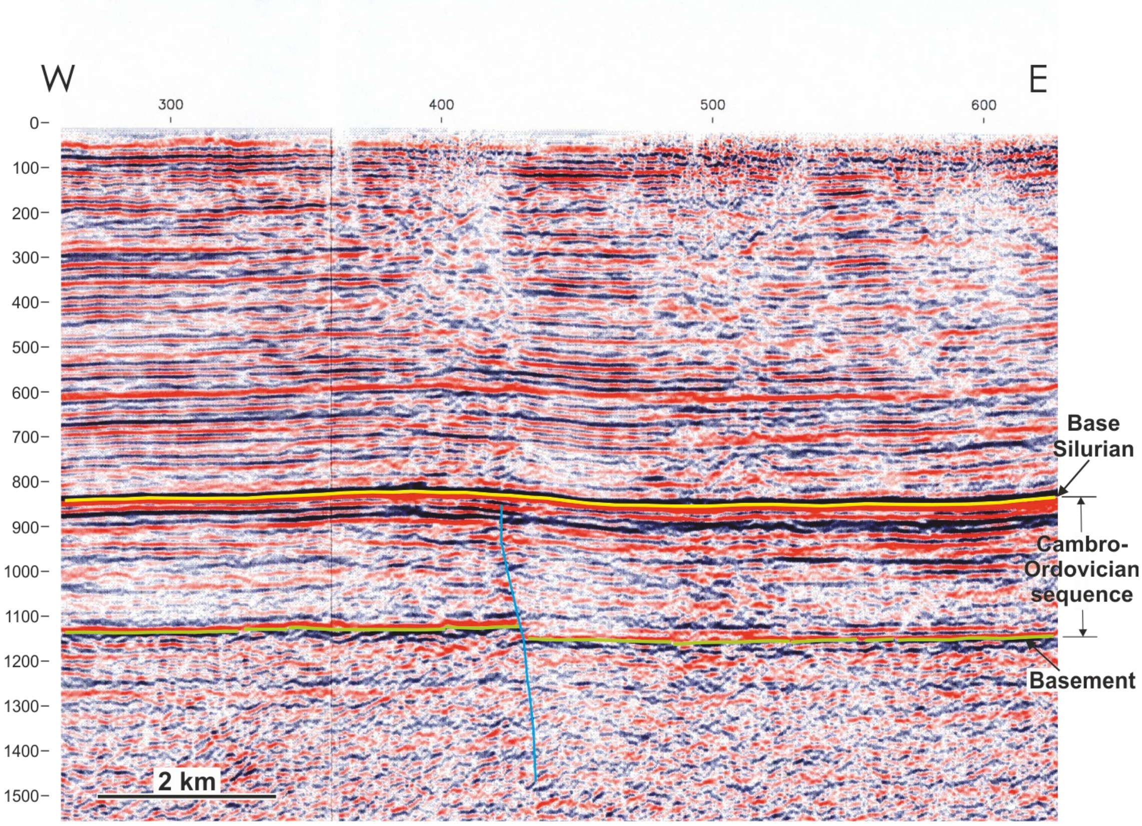


Figure 14.- E-W seismic section in NC186 concession showing Cambro-Ordovician normal faults.

by medium- to coarse-grained cross-bedded sandstones. The lateral extent of the formation in the basin subsurface remains poorly know because most of the wells don't drill down to the basement.

The Early Ordovician extension:

According to Davidson et al. (2000), the earliest recognized structures affecting the sedimentary infill of the basin were faults of Cambro-Ordovician age. Many of these faults were subsequently reactivated by later movements and this can lead to some difficulties in interpretation of Cambro-Ordovician kinematics. A few small displacement features that have not undergone post-Ordovician reactivation can be interpreted as extensional normal faults with thickening of the hanging wall Cambro-Ordovician section. If this interpretation is correct, these are the only purely extensional faults yet recognized in the basin, but with typical minor displacement of less than 100 m (Fig. 14).

More commonly, however, thickening of the Cambro-Ordovician section is observed in the footwall of steeply dipping reverse faults, implying synsedimentary movement of compressional or transpressional origin. Displacements are significant, often with over 100 m thickening across the larger faults.

On the other hand, it must be stressed that Mamgain (1980) refers to the presence of rhyolitic rocks in the western border of the Kufrah Basin. These rocks were dated by K/Ar as Early Ordovician, and constitute the only reference to the presence of Ordovician volcanic rocks in Libya. Later, Ramos et al (2003, 2004b) highlight the presence of volcanic ash beds stratified within the sandstones of the Middle Ordovician Hawaz Fm. These volcanic ash beds derived from a coetaneous explosive volcanism, and formed by calcalkaline acid members potassium-rich. However, it is not clear that this volcanism could be related to extension because their geochemistry is similar to the crustal melt although they preserve the negative anomaly in Ni and Ta that indicate a subduction character (Ramos et al, 2003).

The Late Ordovician glaciation:

During the Late Ordovician times, when Gondwana was located at high latitude (see Fig. 4A), a first-order glaciation took place, covering with a thick ice cap most of the present-day North Africa, from Morocco to the Middle East (Turner et al., 2005; Le Heron et al., 2007; Le Heron and Craig, 2008) and producing a glacially-related erosive surface which extends largely in North Africa, and can be recognized in the whole Murzuq Basin. The movement of the ice sheet from the highlands to the open ocean thorough palaeo-ice streams produced a marked topography by the incision of deep valleys on the underlying pre-Late Ordovician sequences (Fig. 15). According to Le Heron and Craig

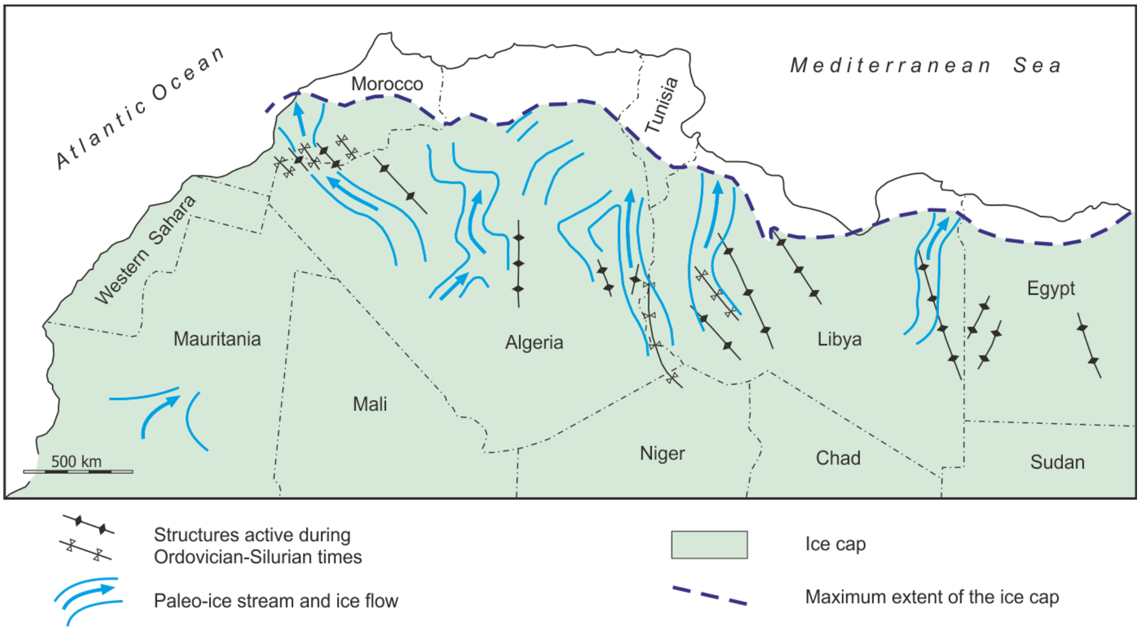


Figure 15.- Palaeo glaciological reconstruction of the Late Ordovician Saharan ice sheet. Redraw from Le Heron and Craig (2008).

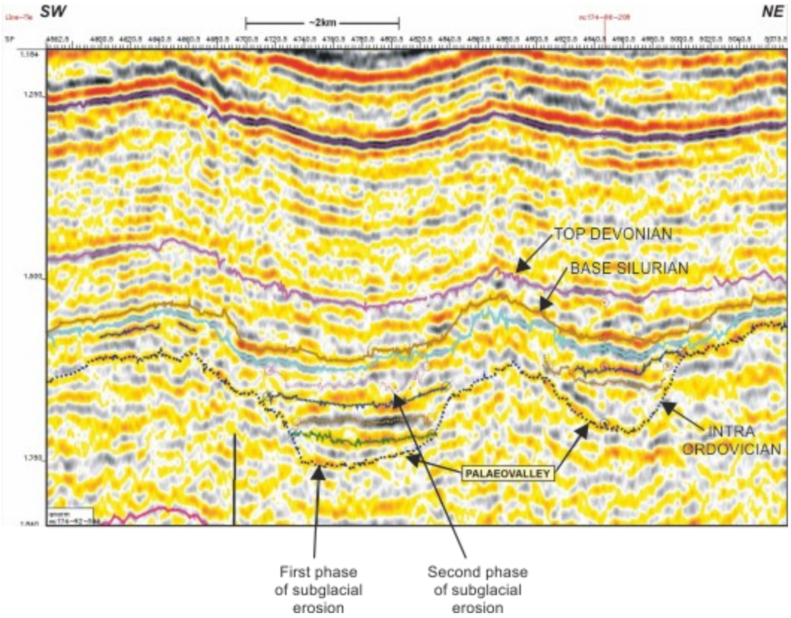


Figure 16.- Seismic section showing the erosive intra-Ordovician surface related with the late Ordovician glaciation. Deposition of syn- and post-glacial sediments was controlled by the resulting palaeotopography. Two sequences related to the expansion – retreating ice-sheet are shown. The seismic section corresponds to the licence NC-174, in the subsurface of the central Muzuq Basin. After Smart (2000).

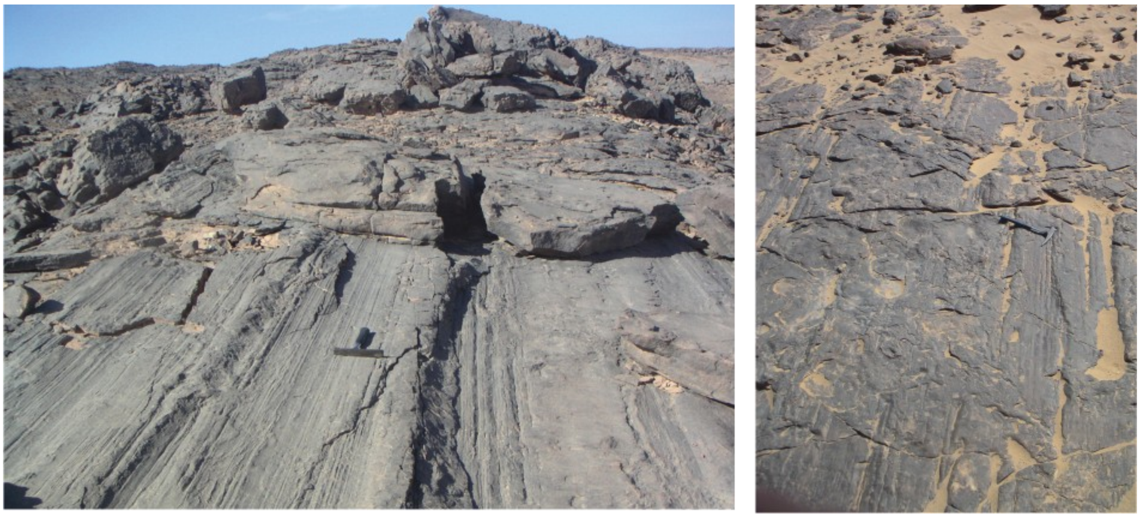


Figure 17.- Glacial striae in the erosive surface related to the late Ordovician glaciation. Images come from the Ordovician outcrops near Ghat, in the Tihemboka high, western Murzuq border.

(2008) these palaeo-ice streams form a drainage system flowing to the NE – NW, having dimensions of 50-600 km length and 50-100 km width, spaced 200 -1000 km apart. Ramos et al (2006) recognized smaller incised palaeo-ice streams by geological mapping of the outcrops in the Gargaf high, whereas that based on seismic data, Aziz (2000), Khoja et al. (2000) and Smart (2000) described similar paleovalleys and paleohighs in the subsurface of the Murzuq Basin (Fig. 16). Ramos et al (2012) higlight the similitude between the glacial Ordovician paleotopography and the Holocene topography developed in the present-day Antarctic margin in a context of glacial retreat. It is widely recognizable glacial erosive features as striated surfaces (Fig. 17) in the entire basin bounding highs as the Gargaf, Tihemboka and Tibesti arches (Deynoux and Ghienne, 2004).

The late Ordovician glaciation is a key feature in the petroleum geology of the Murzuq Basin by two main reasons: Fist because the glacial-related paleotopography controlled the deposition of the syn- and post-glacial sequences, and the periglacial sandstones are important reservoir rocks in the northern Murzuq Basin, where they form part of the oil reservoir in the NC 115 and NC 174 areas and this has been also described in southern Tunisia and Algeria oil fields. And second, because the deeply incised palaeotopography, forming palaeovalleys and palaeohigs constituted one of the main trap mechanism across the Murzuq Basin. Franco et al. (2012) highlight that the glacial-related paleohighs constituted the main trap mechanism in the subsurface of the block NC-186, in the northern Murzuq Basin.

The Caledonian orogeny:

A major basin-scale unconformity, locally with angular unconformity, is recorded within the sedimentary infill separating the Silurian and Devonian sequences (Ca in Fig. 10). According to Davidson et al (2000) this unconformity reflects compressional tectonic movements occurred during Late Silurian to Early Devonian time span (500-380 Ma), when the main structural highs bounding the Murzuq basin were reactivated. Bellini and Massa (1980) state that these movements persisted from Mid- to late Silurian times. El Hawat and Ben Rahuma (2008) point out that during this time three episodes of tectonism could be inferred by vertical movements associated with intrusion of igneous rocks, erosion and formation of angular unconformities on the uplifts bounding the Murzuq Basin. These authors attributed this to the rejuvenation of the former Pan-African structures bounding these major uplifts leading to differential subsidence. The correlation of stratigraphic sections across the Gargaf and Tihemboka arches shows significant thickness reduction, as compared to the subsurface, in the order of several hundred meters, and possibly up to a thousand meters locally. It means that the Upper Ordovician Mamuniyat Fm, the Silurian Tanezzuft shale and the Early Devonian Tadrart Sandstone are thinned or were eroded completely in sections across the Gargaf and Tihemboka uplifts, which were be considered as active source areas during this time (Karasek, 1981). However, it has been also documented by Abugares and Ramaekers (1993), Boote et al (1998) and Aziz (2000) as the Silurian (and locally the basal Devonian) section is missing through erosion at this unconformity in the subsurface of the Murzuq Basin. The thick upper Silurian sandstones of the Akakus Fm., which crops out on the western part of the basin, are absent in some wells in the basin centre, probably due to erosion, that has been estimated of around 250 m in license NC-115 by Aziz (2002). Furthermore, the Caledonian unconformity controls the areal distribution of the Basal Devonian sandstones (BDS) which filled the depressions of the irregular topography created by this erosive surface. Similar arrangement, with a surface eroding much of the Silurian sequence and controlling the deposition of the Devonian strata has been described by Echikh (1998) in the subsurface of the adjacent Ghadamis Basin.

This is a significant feature because a number of the structures forming the present-day traps in the Murzuq Basin were initiated by the Caledonian compression; e.g. the trapping structure of the F1-NC174 discovery was originated by a high-angle reverse fault related to the Caledonian compression (Davidson et al., 2000). These late Silurian – early Devonian faults in the Murzuq Basin vary in trend from NW-SE through N-S to NE-SW, probably following pre-existing Pan-African trends. The NW-SE trending Tripoli-Tibesti uplift had some expression prior to the main late Silurian to early Devonian tectonics, but underwent renewed growth during this time. An important consequence of the movements on this paleohigh is that the Silurian hot shale source rocks is absent from the northeastern part of the Murzuq Basin, probably due to a combination of non-deposition and erosion following the Caledonian reactivation. The geological map of the Murzuq Basin (Fig. 9) shows as Silurian rocks are missing in the northern part of the basin and the southern margin of the Gargaf uplift.

The Hercynian orogeny:

The Hercynian orogeny was a consequence of the collision between Gonwana and Laurasia and the subsequent formation of the short-lived Pangaea supercontinent. The Hercynian tectonism affected the Murzuq Basin from the late Carboniferous (Moscovian) to the Early Permian, covering a time span from about 370 to about 230 Ma. The Hercynian compression resulted in the development of erosive unconformities that can be observed on seismic sections on the crest of the uplifted blocks, where sedimentary sequences of this age are generally thinner or missing, whereas in the footwall sections the Carboniferous sequences are thicker (Davidson et al, 2000).

In North Africa the Hercynian orogeny originated a major zone roughly coincident with the Atlas mobile belt and extends eastwards to north-central Tunisia. Towards the East, it reactivated throughout Libya and Egypt the former Pan-African and Caledonian compressional structures that later became hydrocarbon traps in the Murzuq Basin, and led to the rise of the Gargaf and Atshan archs, which exhibit evidence of Hercynian volcanic activities (Grubic et al., 1991).

The Hercynian orogeny played a significant role in the structural development of the Murzuq Basin by reactivation of the faults bounding structural highs, however, available data suggest that Hercynian tectonism was less important in the development of the basin. No significant regional tilting occurred at this time in Murzuq, in marked contrast to the neighbouring Illezi and Ghadamis basins, were a major angular unconformity can be observed. However, despite the absence of angular unconformity, a significant stratigraphic section does appear to be missing at the Hercynian unconformity in the Murzuq Basin, with several authors in agreement that a part of the Upper Carboniferous and most of the Permian sequence is absent. It is concluded herein that the basin was probably subject to significant regional uplift during late Carboniferous time, resulting in relatively uniform erosion of the Carboniferous succession and non-deposition of Permian sediments (Davidson et al, 2000). However, in the basin subsurface a general trend can be notated, the general thickness of preserved Carboniferous sequence increases northwestwards, while erosion and non-deposition were much stronger in the center and SE of the basin, were the preserved Carboniferous section is much thinner. In the subsurface of the central part of the basin (block NC-115) Aziz (2000) estimates a missing of the Carboniferous section from 1000 to 1800 m.

The Hercynian tectonic phase in the Murzuq Basin is considered a key event as regards timing of hydrocarbon generation. During this tectonic event unconformities developed due to major regressive, lowstand events. These tectonics and tectonically induced lowstand events have had a significant impact on the development of the hydrocarbon potential of the Murzuq Basin.

3.2. PALAEOZOIC LITHOSTRATIGRAPHY:

There is not a general agreement about the lithostratigraphic units which constitutes the Palaeozoic sedimentary infill of the Murzuq Basin nor their correlation. A summary and attempt of correlation for the proposals of previous workers (i.e. Mamgain, 1980; Aziz, 2000; Davidson et al, 2000; Echikh and Sola, 2000; Ramos et al, 2006; El Hawat and Rahuma, 2008) is shown in figure 18. In this work, we assumed the lithostratigraphic subdivision proposed in figure 19 which will be detailed in the next sections.

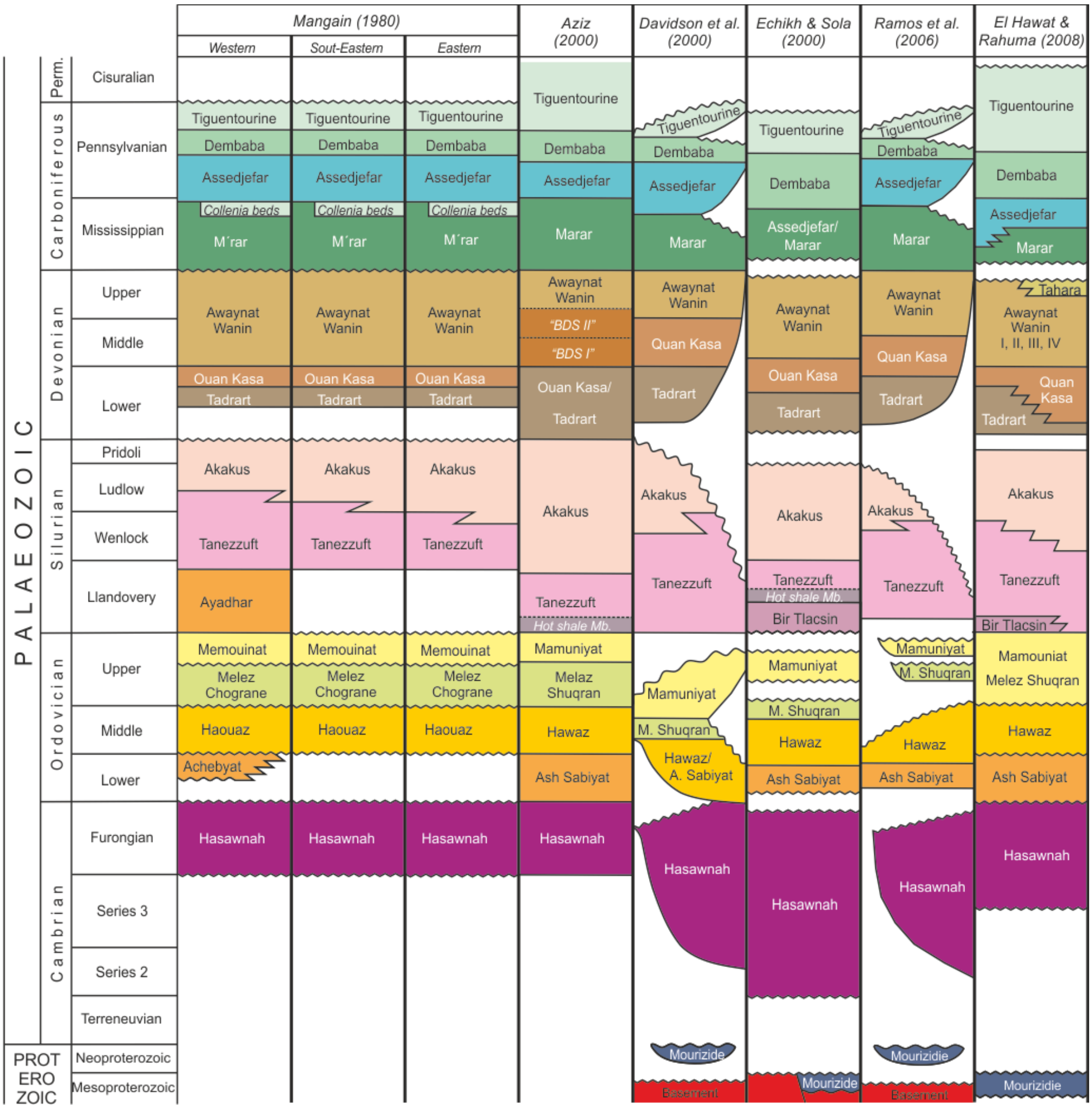


Figure 18.- Proposal of correlation of the lithostratigraphic chart proposed by different previous workers for the Murzuq Basin. See text for explanation.

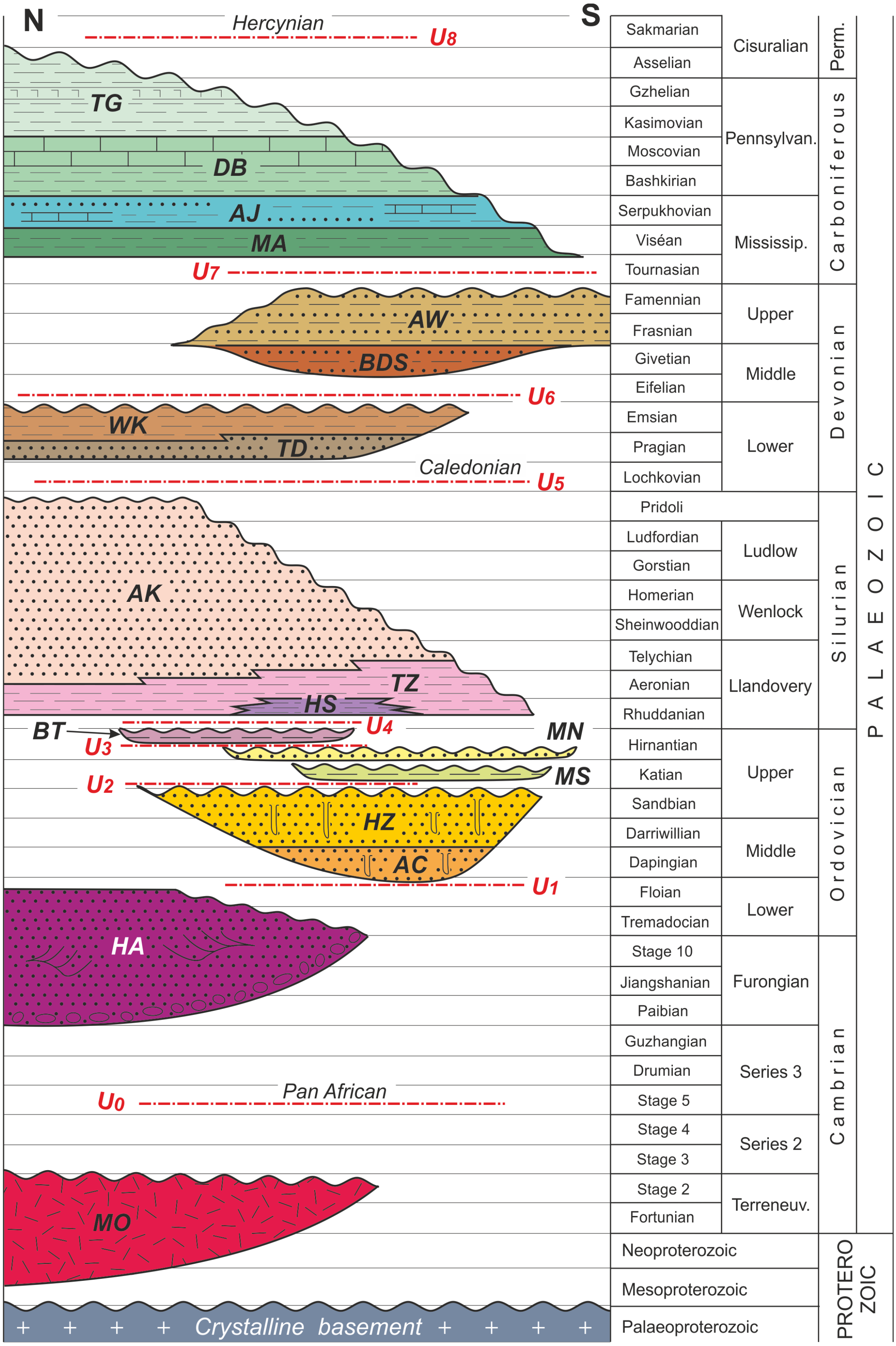

N
Hercynian
S
U8
TG
DB
AJ
MA
U7
AW
BDS
U6
WK
TD
Caledonian
U5
AK
TZ
HS
BT
U4
MN
U3
MS
U2
HZ
AC
U1
HA
U0
Pan African
MO
Crystalline basement
Sakmarian
Asselian
Cisuralian
Perm.
Gzhelian
Kasimovian
Moscovian
Bashkirian
Pennsylvan.
Serpukhovian
Viséan
Tournasian
Mississip.
Carboniferous
Famennian
Frasnian
Upper
Givetian
Eifelian
Middle
Emsian
Pragian
Lochkovian
Lower
Devonian
Pridoli
Ludfordian
Gorstian
Ludlow
Homerian
Sheinwooddian
Wenlock
Telychian
Aeronian
Rhuddanian
Llandovery
Silurian
Hirnantian
Katian
Sandbian
Upper
Darriwillian
Dapingian
Middle
Floian
Tremadocian
Lower
Ordovician
Stage 10
Jiangshanian
Paibian
Furongian
Guzhangian
Drumian
Stage 5
Series 3
Stage 4
Stage 3
Series 2
Stage 2
Fortunian
Terreneuv.
Cambrian
PALAEOZOIC
Neoproterozoic
Mesoproterozoic
Palaeoproterozoic
PROTERO ZOIC

Figure 19.- Lithostratigraphic chart and major basin-scale unconformities proposed in this work for the Palaeozoic sedimentary infill of the Murzuq Basin. **U_0** to **U_8** = Unconformities. **MO** = Mourizide Fm.; **HA** = Hasawnah Fm.; **AC** = Achabiyat Fm.; **HZ** = Hawaz Fm.; **MS** = Melaz Suqran Fm.; **MN** = Mamuniyat Fm.; **BT** = Bir Tlacsin Fm.; **HS** = Hot Shales Mb. **TZ** = Tanezzuft Fm.; **AK** = Akakus Fm.; **TD** = Tadrart Fm.; **WK** = Wan Kasa Fm.; **BDS** = Basal Devonian Sandstones Mb. **AW** = Awainat Wanin Fm.; **MA** = Marar Fm.; **AJ** = Assedjefar Fm.; **DB** = Dembaba Fm. and **TG** = Tiguentounine Fm.

So, we divided the Palaeozoic sedimentary infill of the Murzuq Basin in the following fifteen lithostratigraphic units:

1) Hasawnah Formation
2) Achabiyat Formation
3) Hawaz Formation
4) Melaz Suqran Formation
5) Mamuniyat Formation
6) Bir Tlacsin Formation
7) Tanezzuft Formation
8) Akakus Formation
9) Tadrart Formation
10) Wan Kasa Formation
11) Awainat Wanin Formation
12) Marar Formation
13) Assedjefar Formation
14) Dembaba Formation
15) Tiguentounine Formation

The Tiguentounine Formation is considered as the record of deposition during the upper Carboniferous to lowermost Permian time span. In general, Permian strata are missing in the Murzuq Basin because it is assumed that during this period took place the main phase of Hercynian uplift and erosion in the area (Echikh and Sola, 2000) and the whole of the Permian deposits were removed. The estimated erosion produced by the Hercinyan uplift strongly varies, from as little as 300 m proposed by Davidson et al (2000) to over 2000 m calculated by Aziz (2000).

3.2.1. Hasawnah Formation:

The Hasawnah Formation was first defined by Massa and Collomb (1960) in the Jabal Al Hasawnah, in the Gargaf high, where it crops out extensively occupying most of the eastern Gargaf, but no type section was defined in this zone. In the type area the formation is 350-400 m thick and rests unconformable over the Precambrian granites of the basement which crops out forming small inliers (Jurák, 1978). It constitutes a detrital sequence mainly made of medium- to coarse-grained, cross-bedded sandstones and subordinate conglomerates and shales. Sandstones of the Hasawnah section in the type area are unbioturbated except in its upper part were scarce *Skolithos* and *Cruziana* trace fossils developed. In the type area the top of the Hasawnah Formation is not clearly observable, however, Klitzsch (1963) refers an angular unconformity between the Hasawnah and the overlaying Ordovician units, but Mamgain (1980) considers that this angular unconformity is not clear in other parts of the Murzuq basin, and this author suggests that the angular unconformity on top of the Hasawnah Formation could be a local feature. However, Tawengi et al, (2012) documented in the neighbouring Kufrah Basin an unconformity on top of the Hasawnah Formation.

On the basis of their lithology and facies, Cepek (1980) divided the Hasawnah Formation in three units (Fig. 20). The lower Hasawnah unit is made by a thin but variable in thiknnes basal lag of quarzitic conglomerates grading upwards to massive to cross-bedded middle- to coarse-grained sandstones interstratified wit thin conglomeratic beds and forming finning- and thinning-upwards sequences. The middle unit is formed by fine-grained silty sandstones interstratified whit thin siltstone beds. The upper unit of the formation is dominantly composed of cross-bedded sandstones containing scarce *Skolithos* and *Cruziana* trace fossil, although locally the bioturbation degree could be intensive. The sandstone of the Hasawnah Formation is feldespathic, and contain kaolinite matrix.

Regardless of the above mentioned trace fossils, no macrofossil content has been reported from the Hasawnah Formation. The unique fossil record yielded for the Hasawnah Formation is palynoflora (acritarchs) remains. According to Miles (2001) the palynoflora fossil content in the studied Hasawnah samples is scarce and probably derived from mud drilling contamination, however, one core sample from the upper part of the Hasawnah Formation drilled by well H27-NC115, in the subsurface of the northern Murzuq Basin, is characterized by the presence of *Velatachitina* spp. and *Frankea breviuscula* that seem to be in situ, indicating an age of Llanvirnian – Middle Arenigian (according to the British series) that it means, a middle Ordovician age. On the other hand, Mamgain (1980) synthesizes K/Ar and Rb/Sr radiometric data derived from Pan-African granitic and pegmatitic intrusions, which provide absolute ages ranging from 501 to 595 My (late Pecambrian – middle Cambrian),

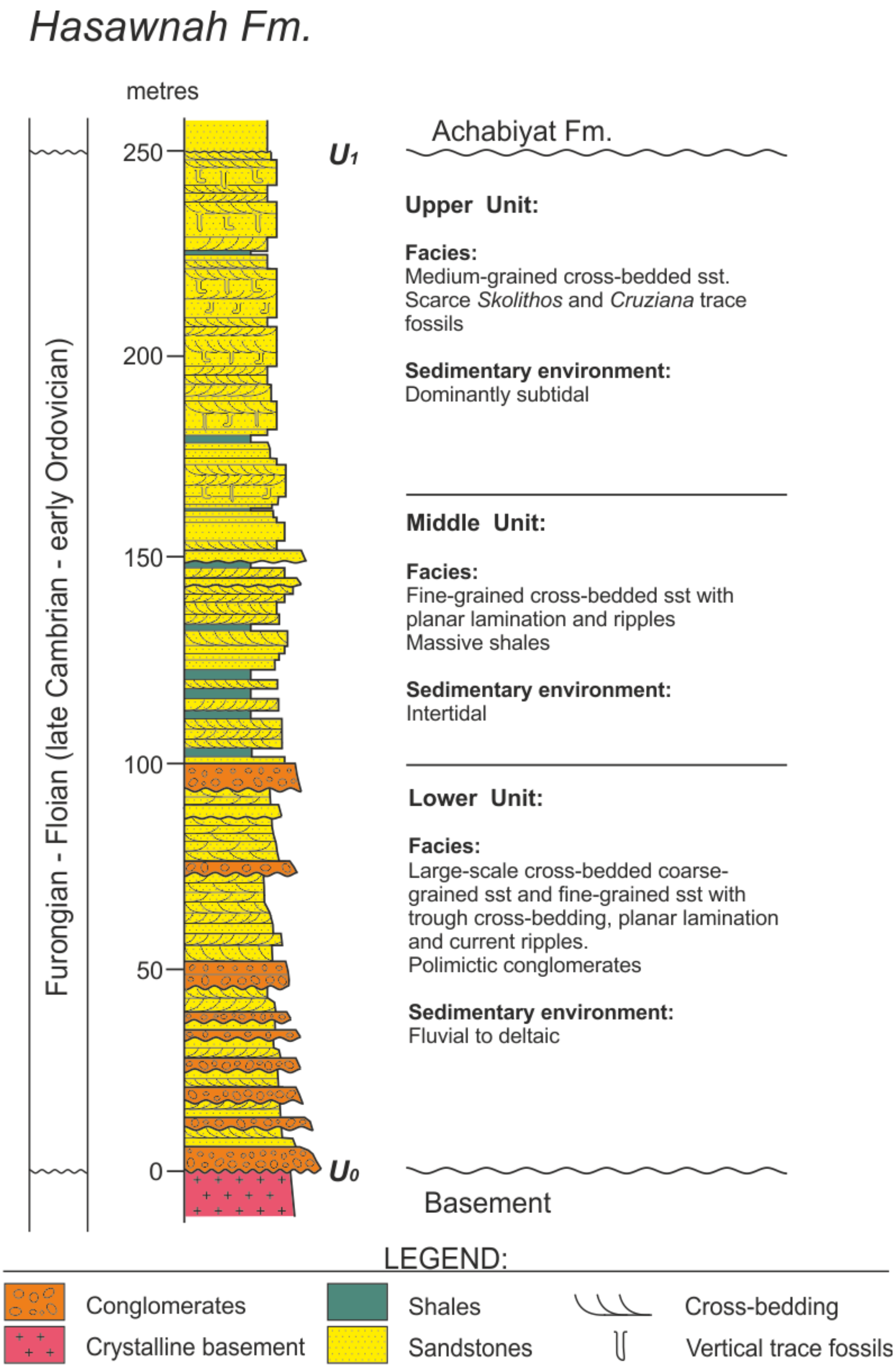


Figure 20.- Stratigraphic log for the Hasawnah Formation based on the composite section compiled by Cepek (1980) in the Jabal Hasawnah type area, eastern Gargaf. U_0 and U_1 are basin-scale unconformities shown in Fig.19.

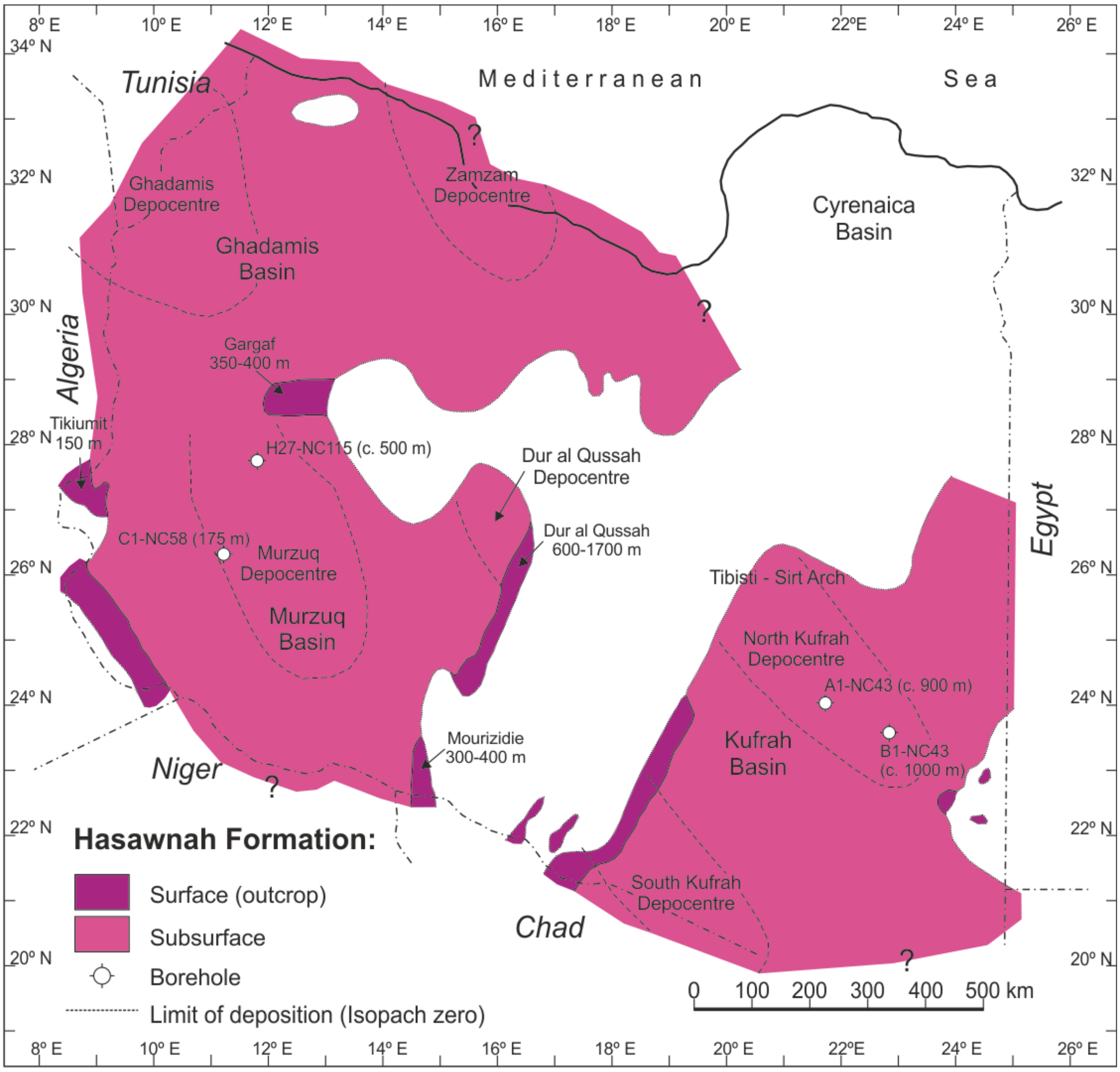


Figure 21.- Outcrop and subsurface extents of the Hasawnah Formation in Libya. Redraw from Hallett (2002).

because this, the overlying Hasawnah strata are considered by many authors as late Cambrian in age. So, we proposed for the Hasawnah Formation a late Cambrian – middle Ordovician age.

The Hasawnah Formation is an extensive unit present in most of the Libyan basins (Fig. 21). In the Murzuq basin crops out in the boundaries of the basin, but it is absent, probably by erosion, in the Tihemboka and Tibesti highs. In the Gargaf high it reach the above mentioned 350-400 m in thickness; in the Tikiumit area (western Murzuq Basin) about 150 m of Hasawnah succession has been reported, and in the Dur al Qussah area (eastern Murzuq Basin) sections reaching up to 1700 m in thickness have been measured. The Hasawnah Formation extends over much of the subsurface across the Murzuq basin, where it depocenter is defined. Well C1-NC 58 drilled a 175 m thick

Hasawnah succession, and northerly; in the block NC115 it has been reported reaching thicknesses ranging from 310 m (well M1) to 495 m (well H27).

The Hasawnah Formation is present in other Palaeozoic basins in Libya. Tawengi et al. (2012) reported abundant data about this unit in the whole of the Kufrah Basin, where a thick succession crops out. In the Kufrah Basin the Hasawnah Formation is clearly continental (fluvial), shows lateral variations, trending from a proximal braided fluvial system in the SE to a distal meandering fluvial system to the NW, displaying a thickener of the unit in the same direction.

According to Cepek (1980) the lower unit of the formation records detrital deposition in a fluvial to deltaic environment (Fig. 20), ranging progressively to intertidal in the middle unit and subtidal conditions in the upper unit. These palaeoenvironmental conditions are in agreement with the palynoflora content, which suggest a fluvial depositional environment ranging to proximal marine in their upper part (Miles (2001). So, the Hasawnah Formation constituted a regressive-transgressive sequence, recording fluvial and deltaic progradation followed by a marine transgression forming a deepening-upward sequence.

As the Hasawnah Formation is not an important reservoir in the Murzuq Basin, there are not available petrophysics data for these rocks. The unique available petrophysical data of the Hasawnah sandstones derived from the Kufrah Basin, where Tawengi et al. (2012) measured, on the outcropping sandstones, porosity values averaging from 16.9% (for the proximal Hasawnah sandstones) to 19.4% (for the distal ones). The measured permeability of these rocks is high, around 1400 mD.

3.2.2. Achabiyat Formation:

Originally Massa and Collomb (1960) defined the Hawaz Formation as the entire sandy Ordovician succession outcropping in the Gargaf area and bounded by two unconformities developed on top the Hasawnah Formation and below the Melaz Suqran and/or the Mamuniyat formations. Later, Collomb (1962) subdivided the former Hawaz Formation in three members: a) "*Tigillites* inferieurs", b) "Gres intermediaries" and c) "*Tigillites* superieurs", and finally, Havlicek and Massa (1973) introduced the term Achabiyat Formation for the lower part –possibly the "*Tigillites* inferieurs" and part of the "Gres intermediaries"- of Collomb's (1962) subdivision. In this way, the original Hawaz Formation of Massa and Collomb (1960) was subdivided in two new conformable formations named Achabiyat (the lower) and Hawaz (the upper). Although no type section was defined, the Formation takes its name from the Jabal Achabiyat, in the eastern Murzuq basin, which is considered its type area. In subsurface and locally in outcrop, the distinction between the two formations is not clear and sometimes the subsurface data don't differentiated between the Achabiyat and the Hawaz formations. In the Geological map of Libya, Gundobin (1985) and Parizek et al (1984) put forward a 65 m thick composite section for the Jabal Achabiyat type area (Fig. 22) In the type area the Achabiyat Formation unconformably overlays the Hasawnah Formation, whereas the top is a conformable contact with the Hawaz Formation. It has been divided in two unitsforming a gradual coarsening and shallowing-upwards succession (Fig. 22).

Lithologically the Formation is formed by a quartzarenitic package. The lower unit ranges between 15 and 30 m in thickness and mainly consists of siltstones and thinly parallel bedded fine-grained sandstones often ferruginous containing abundance of *Skolithos* and scarce *Cruziana* trace fossils. Cross-bedding and other tractive structures are rare. The upper unit is massive to thickly bedded and more extensively cross-bedded, bearing some similarity to the Hasawnah Fm. It consist in medium- to coarse-grained, poorly sorted sandstones, occasionally conglomeratic, grading upwards to well sorted fine-grained sandstones. The samples from well H15-NC115 used by palynological study result barren (Miles, 2001), because the age of this unit is established as Arenigian – Lanvirnian (Lower – Middle Ordovician; Floian – Darriwilian in the standard stages) on the basis of their stratigraphical position.

The Achabiyat Formation crops out in the Gargaf, Tihemboka and Tibesti highs, where it displays similar characteristics, although in the Tibesti the formation has not been differentiated from the overlaying Hawaz Formation. Thickness shows no great variations; in the Gargaf the unit reach the above mentioned 65 m in thickness, whereas in the Tihemboka area it reach 50 m thick in Tikiumit, 60 m in Ghat and 70 m thick in Wadi Tanzuft locations. The formation extends across the subsurface of the western Murzuq Basin (Fig.

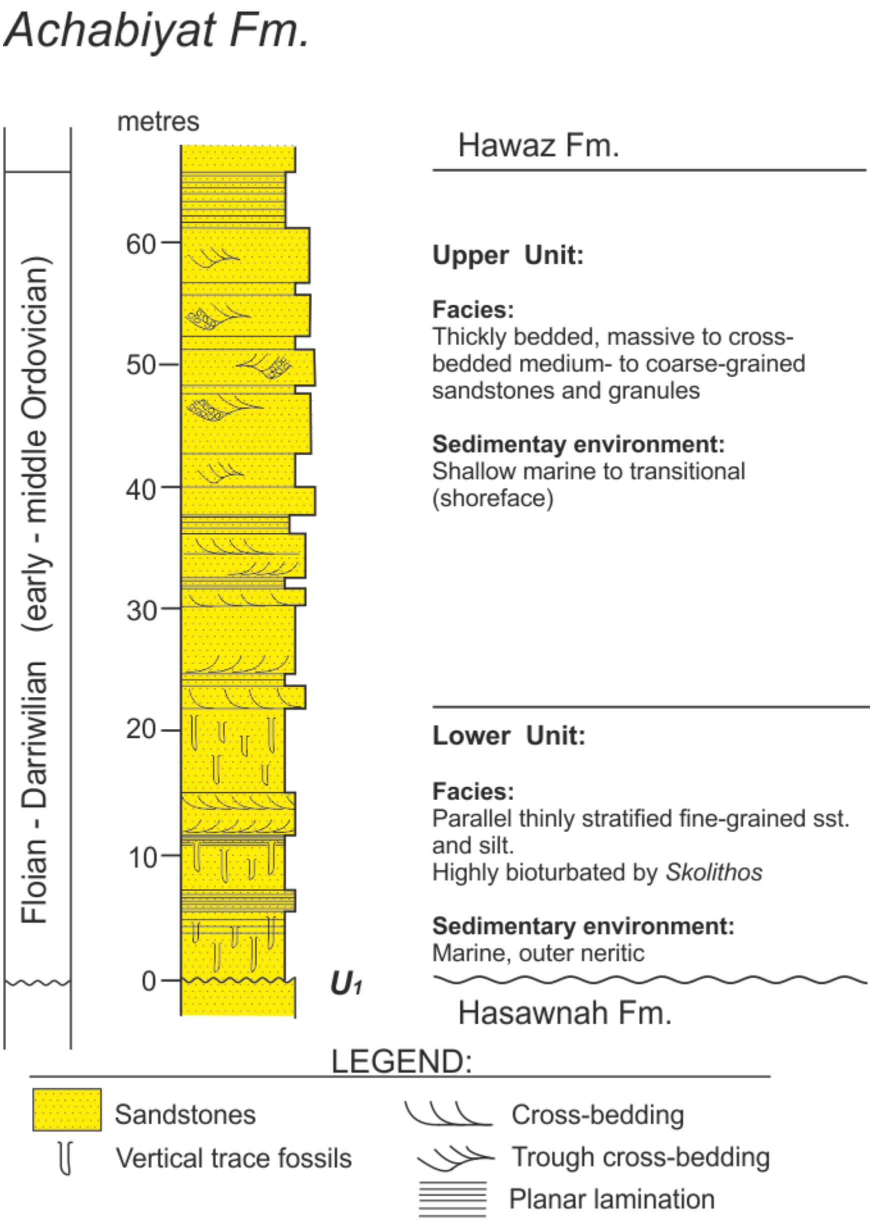


Figure 22.- Composite stratigraphic section for the Achabiyat Formation compiled by Gundobin (1985) and Parizeq et al (1984) in the western Gargaf area. Surface U_1 represent the basin-scale unconformity shown in Fig.19.

23), suggesting the existence of a depocenter in the central Murzuq, but in spite that a number of wells cut the unit, it has not possible to draw accurately this depocenter because of the fact that in the subsurface wells not discriminated between Achabiyat and Hawaz formations. The Achabiyat Formation is also present in Ghadamis and Hamra Basins, but it is absent by erosion in Cyrenaica and Kufrah Basins.

The Achabiyat Formation records deposition in a marine setting, where the fine-grained silty sandstones highly bioturbated of their lower unit are interpreted as deposited in a outer neritic environment, grading upwards to the unbioturbated coarse-grained sandstones of the upper unit indicating deposition in a shallow marine to transitional (shoreface) environment. In brief, the Achabiyat Formation is interpreted as the result of a deeper water pulse, between the Hasawnah and the Hawaz formations where the fine-grained and highly bioturbated sediments of the lower unit represent a maximum marine flooding interval in the basin (Hallet, 2002).

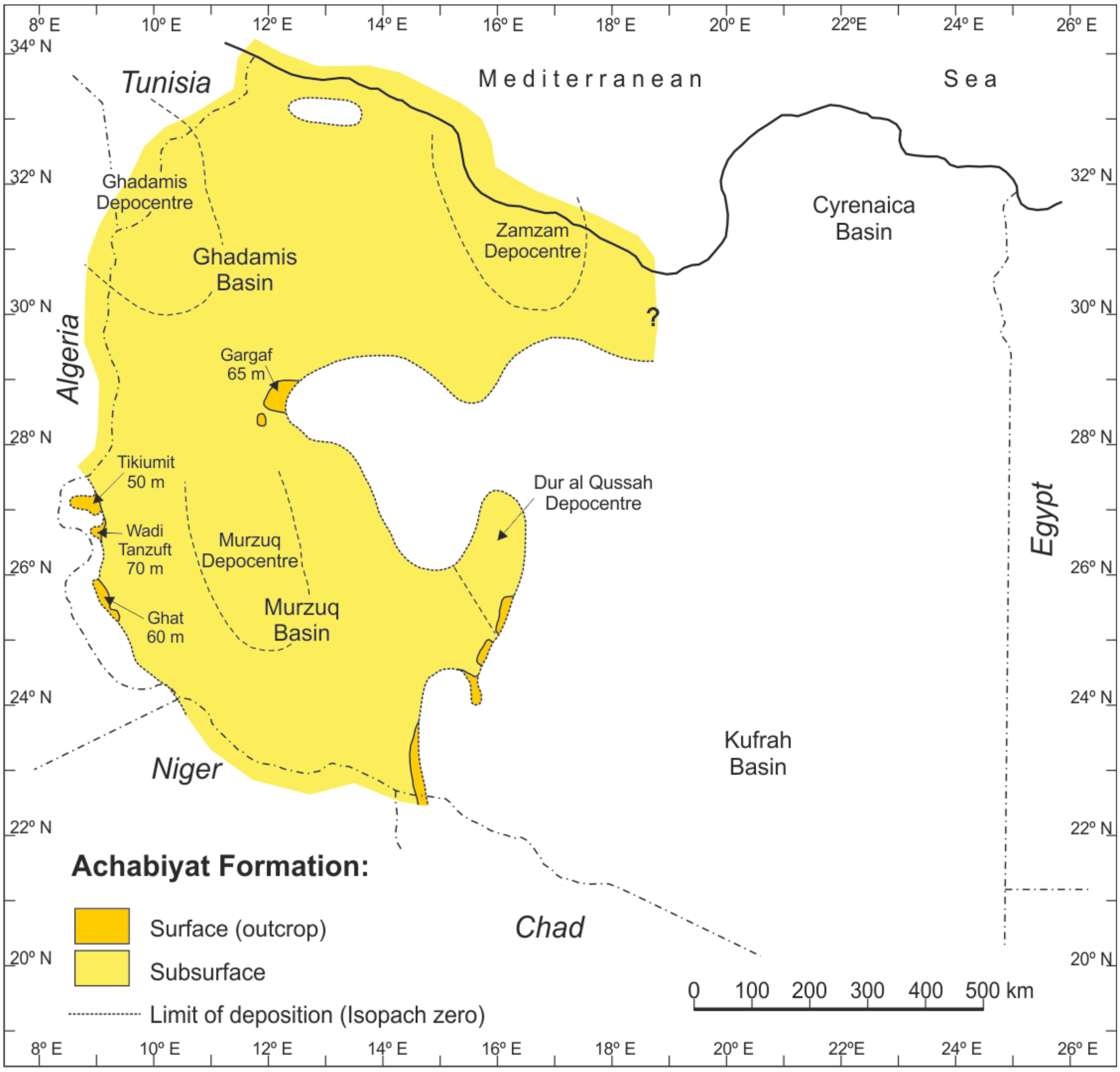


Figure 23.- Outcrop and subsurface extents of the Achabiyat Formation in Libya. Redraw from Hallett (2002).

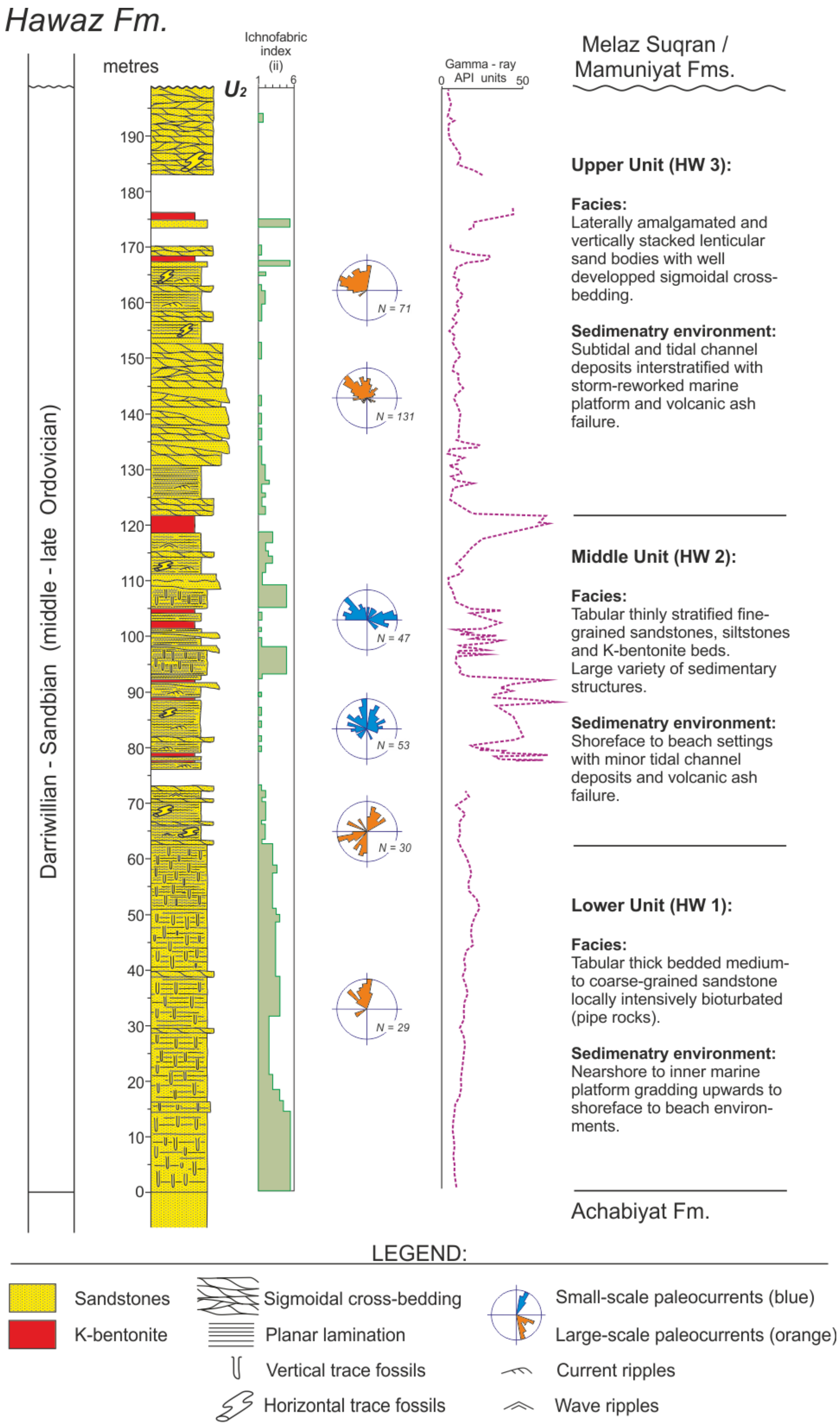
3.2.3. Hawaz Formation:

The Hawaz Formation was originally defined by Massa and Collomb (1960) as the entire sandy Ordovician succession outcropping in the Gargaf area and bounded by two unconformities developed on top the Hasawnah Formation and below the Melaz Suqran and/or the Mamuniyat formations. Collomb (1962) subdivided the Hawaz Formation in three members: a) “Tigillites inferieurs”, b) “Gres intermediaries” and c) “Tigillites superieurs”. Later, Havlicek and Massa (1973) introduced the term Achabiyat Formation for the lower part –possibly the “Tigillites inferieurs” and part of the “Gres intermediaries”- of Collomb’s (1962) subdivision. In this way, the original Hawaz Formation of Massa and Collomb (1960) was subdivided in two new conformable formations named Achabiyat and Hawaz. Although the boundary between the Achabiyat and Hawaz Formations was not clearly established by Havlicek and Massa (1973) our study follows the subdivision proposed by these two authors. This option has also been adopted in the Geological Map of Libya (Parizek et al., 1984; Gundobin, 1985) and by other authors (i.e. Mamgain, 1980; Boote et al., 1998; Echikh, 1998; Aziz, 2000; Echikh and Sola., 2000; Craik et al., 2001 and Hallet, 2002) but contrasts with the opinion of other authors (i.e. Crossley and McDougall, 1998; Davidson et al., 2000; Khoja et al., 2000, and McDougall and Martin, 2000) that prefer to follow the original definition of the Hawaz Formation proposed by Massa and Collomb (1960). Davidson et al. (2000) have suggested that towards the SW (Tihemboka high) the Achabiyat Formation and the Hawaz Formation are laterally equivalent.

A composite, type section for the Hawaz Formation has been proposed by Marzo and Ramos (2003) and Ramos et al. (2006) from correlation of 5 partial sections for the western Gargaf (Fig. 24). In the western Gargaf the Hawaz composite section has a minimum thickness of 197 m. In addition to the lithologic log, figure 24 includes paleocurrent trends, ichnofabric index and the gamma-ray log measured in outcrop. Taking into account lithological and bioturbation characteristics as well as the geometry of the sedimentary bodies, Marzo and Ramos (2003) subdivided the Hawaz Formation into four mappable lithostratigraphic units, which from base to top were called: Basal, Lower, Middle and Upper units. Later, Ramos et al. (2006) merged the Middle and Upper units in a unique Upper unit, resulting subdivided the Hawaz Formation in three units, as shown in figure 24.

The lower boundary of the Hawaz Formation is a conformable contact with the Achabiyat Formation, although in some localities (i.e. in some wells of concession NC115) it rest unconformable directly on the basement rocks.

The upper boundary of the Hawaz Formation is formed by two glaciogenic erosive surfaces named U_1 and U_2 (Fig. 25). The older unconformity (U_1) underlies the Melaz Suqran Formation; the younger unconformity (U_2) consti-



Upper Unit (HW 3):

Facies:
Laterally amalgamated and vertically stacked lenticular sand bodies with well developped sigmoidal cross-bedding.

Sedimenatry environment:
Subtidal and tidal channel deposits interstratified with storm-reworked marine platform and volcanic ash failure.

Middle Unit (HW 2):

Facies:
Tabular thinly stratified fine-grained sandstones, siltstones and K-bentonite beds.
Large variety of sedimentary structures.

Sedimenatry environment:
Shoreface to beach settings with minor tidal channel deposits and volcanic ash failure.

Lower Unit (HW 1):

Facies:
Tabular thick bedded medium- to coarse-grained sandstone locally intensively bioturbated (pipe rocks).

Sedimenatry environment:
Nearshore to inner marine platform gradding upwards to shoreface to beach environments.

Figure 24.- Composite stratigraphic section for the Hawaz Formation compiled by Marzo and Ramos (2003) for the western Gargaf. The ichnofacies log indicates the degree of bioturbation according to Droser and Bottjer (1986). The gamma-ray log was measured directly in outcrop by means of a portable gamma-ray device. Surface U_2 represent the basin-scale unconformity shown in Fig. 19.

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tutes the basal boundary of the Mamuniyat Formation. In the western Gargaf the lower and older unconformity U_1 constitutes the upper boundary of the Hawaz Formation; it is characterised by topographic irregularities, eroding the top of the outcropping Hawaz Formation. The lows related to these topographic irregularities are filled by the Melaz Suqran Formation, which onlaps the erosive surface. The upper and younger unconformity (U_2) is also an erosive surface, in this case underlying the Mamuniyat Formation, which may locally truncate the older U_1 (Fig. 25). In this case, the unconformity U_2 constitutes a unique unconformity, sum of U_1 plus U_2, and the Mamuniyat Formation directly rests on the Hawaz Formation. Geological mapping in the western Gargaf shows as the magnitude of the erosional hiatus linked to the unconformity U_2 (when this is the sum of U_1 plus U_2) varies from west to east. To the west of the Hawaz outcrops, this hiatus includes the whole of the Melaz Suqran Formation and a part of the Upper Hawaz unit. In the central part of the Hawaz outcrops the hiatus includes the totality of the Upper unit, so that the Mamuniyat Formation directly overlies the Middle Hawaz unit. To the east the hiatus can include the whole Hawaz Formation, resulting in a direct contact between the Mamuniyat Formation on the Achabiyat Formation. Based on subsurface data, Khoja et al. (2000) concluded that this erosive glacial period led to the excavation of NNW-SSE trending, deeply incised palaeovalleys, up to 30 km wide and 300 m deep (Fig. 16).

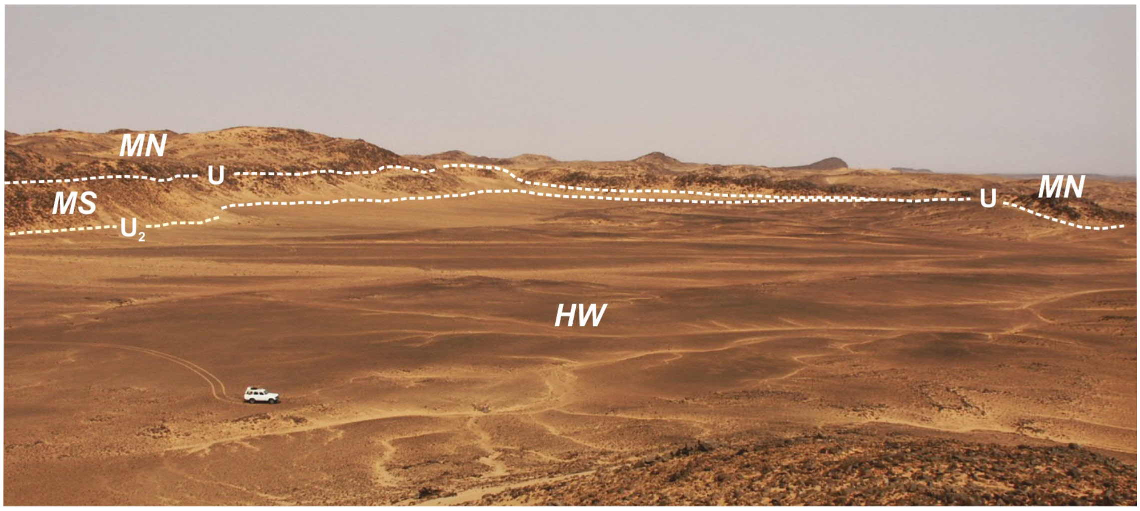


Figure 25.- Field view in the western Gargaf of the erosive surfaces on top of the Hawaz Formation. U_2 and U = unconformities shown in Fig. 19. **HW** = Hawaz Fm. **MS** = Melaz Suqram Fm. **MN** = Mamuniyat Fm.

According to Ramos et al. (2006), the Hawaz Formation is mostly composed of well-stratified sandstones with minor intercalations of silty shales, and a number of k-bentonite beds. Trace fossils are frequent and, locally, abundant enough to overprint most primary sedimentary structures.

Petrography of the Hawaz sandstones indicate that they are quartzarenites (Ramos et al, 2004a; Abouessa and Morad, 2009) The major detrital constituent of the Hawaz sandstones is quartz (Fig. 26). Feldspar grains are scarce, as are heavy mineral grains, whose major constituent is mica. Other heavy minerals observed include well rounded zircon, garnet, tourmaline and rutile grains. The modal composition ranges between Qm_{91},F_0,Lt_9 and Qm_{29},F_2,Lt_{69}, considering as Qm only the monocrystalline quartz grains, and the polycrystalline (2-3 or >3) quartz grains as lithic components (Lt). Some samples show a variety of constituents, whereas other ones are exclusively composed of mono- and 2-3 polycrystalline (Q+Qp) quartz grains.

Up to four cement phases have also been observed in the Hawaz sandstones. The most widely distributed is a sintaxial silica overgrowth (Fig. 26.A, B). Figure 27 is a SEM image showing the characteristic euhedral aspect of the overgrown quartz grains, as well as the resulting intercrystalline/ interparticle porosity. Locally, a second phase of siderite cement generation took place. The siderite cement is scarce and consists of laminae coating the quartz (silica overgrown or not) grains. A third phase of cementation was produced by clay neoformation, which reduced the remaining macroporosity (Fig. 26.C, E). SEM images (Fig. 26.E) allow us to observe the clay cement as formed by euhedral crystals of neoformed clays. EDS analysis, shows a kaolinite composition for these clay minerals, although illite neoformation has been also cited by Abouessa and Morad (2009). Finally, some of the studied samples a fourth cement phase composed of carbonate (probably dolomitic) cement has been observed occluding the porosity. It should be stressed that silica and clay (kaolinite) cements have been observed in all the studied samples, whereas the ferruginous and carbonate cements only appear scarcely. So, it seems probable that siderite and carbonate cementation had a more restricted development than the silica, kaolinite and illite cements.

Interbedded with the sandstones, a number of clay-rich beds, interpreted as k-bentonite have been recognized. Bentonite is a general term used to describe ancient unstable volcanic ash deposits later alterated to clay-rich rocks. Due to their origin from volcanic ash fallout, these deposits form thin but laterally continuous beds. Volcanic ash related to subaerial volcanic eruptions can accumulated in both terrestrial and marine environments, and their resultant bentonite beds have been recognized worldwide intercalated with shallow marine, lacustrine and subaerial sedimentary deposits (Bohor et al., 1979; Huff et al., 1996; Roen and Hosterman, 1982).

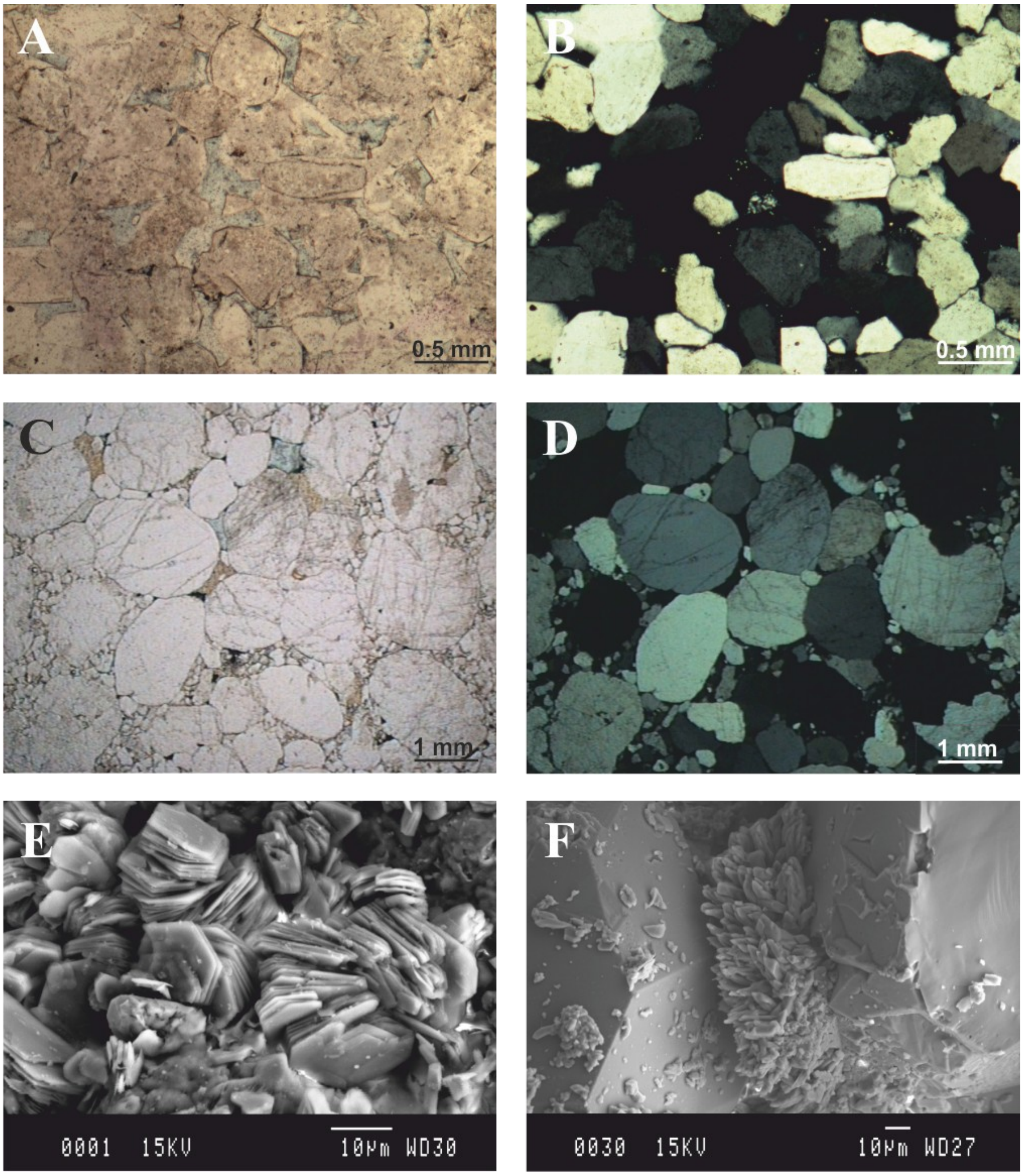


Figure 26.- Petrographic images of the Hawaz Formation sandstones. **A, B** = Plane-polarized light (A) and crossed polars (B) of a fine- to medium-grained quartzarenite showing abundant quartz overgrowth sintaxial cement. **C, D** = Plane-polarized light (C) and crossed polars (D) of a coarse-grained quartzarenite containing clay cement. **E, F** = SEM images of clay cement (kaolinite) (E) and carbonate cement (dolomite) (F).

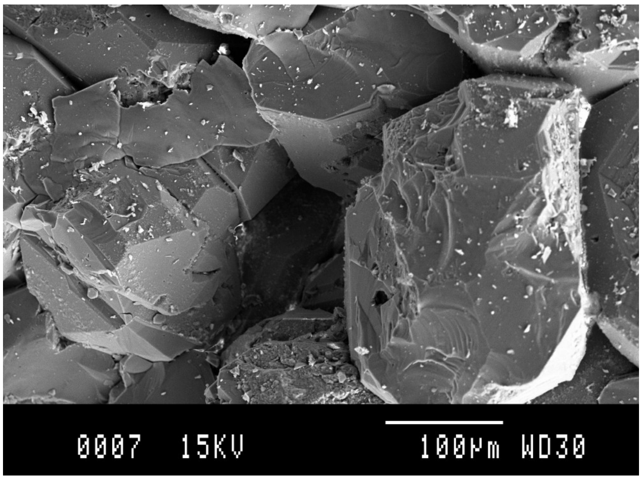


Figure 27.- SEM image of the inter-crystalline porosity within the silica overgrowth quartz grains from the Hawaz Formation.

The lower Hawaz unit is characterized by tabular thick beds of medium- to coarse-grained sandstones. Bioturbation is intensive through most of the unit, forming a pipe-rock (Fig. 28.A) constituted by closely spaced *Skolithos* burrows. *Thalassinoides* and *Teichichnus* trace fossils are also found, but only in the lowermost part of the unit. The lower unit displays a thinning-upwards trend with the pipe-rock sandstones alternating upwards with tabular thinly bedded medium- to fine-grained sandstones (Fig. 28.B, C). Gamma-ray values for this unit have been measured in the field (Fig. 24). The log records low values, especially towards the lower part when associated with medium- to coarse-grained clean sandstones. The progressive upwards increase in gamma-ray values records the slightly fining-upwards trend of the unit.

The middle Hawaz unit (Fig. 24) is mostly formed by tabular and laterally continuous, thinly stratified fine-grained sandstone with subordinate siltstone, intercalating thin K-bentonite beds and occasionally slightly coarser grained lenticular sand bodies. The tabular thin-bedded sandstones include a large variety of sedimentary structures, such as swaley to hummocky cross bedding, planar lamination, large-scale cross bedding, current and wave-ripple cross-lamination, and flasser and linsen structures. In general, the thinly-stratified laminated sandstones of the middle unit show low bioturbation degree because trace fossils are mostly horizontal and restricted to bedding planes. *Cruziana* and *Rusophycus* (Fig. 29.A, B) are the dominant trace fossils, but *Planolites*, *Arthrophycus* (Fig. 29.C) and *Lockeia* are also present, and Seilacher (2000) refers the presence of *Daedalus multiplex* from outcrops soutwards of Ghat. The gamma-ray log of this unit reflects the heterolithic nature of the succession. The lower values corresponds to the well-shorted sandstones, the cross-bedded sandstones containing mud chips have intermediate values, whereas the K-bentonite beds are responsible for the highest radiation peaks.

The upper Hawaz unit (Fig. 24) constitutes a thick, sandstone-dominated package mainly formed by laterally amalgamated and vertically stacked, lenticular, fine- to medium-grained sandstone bodies showing either a massive internal structure or well developed, sigmoidal cross-bedding (Fig. 28.D-F). It

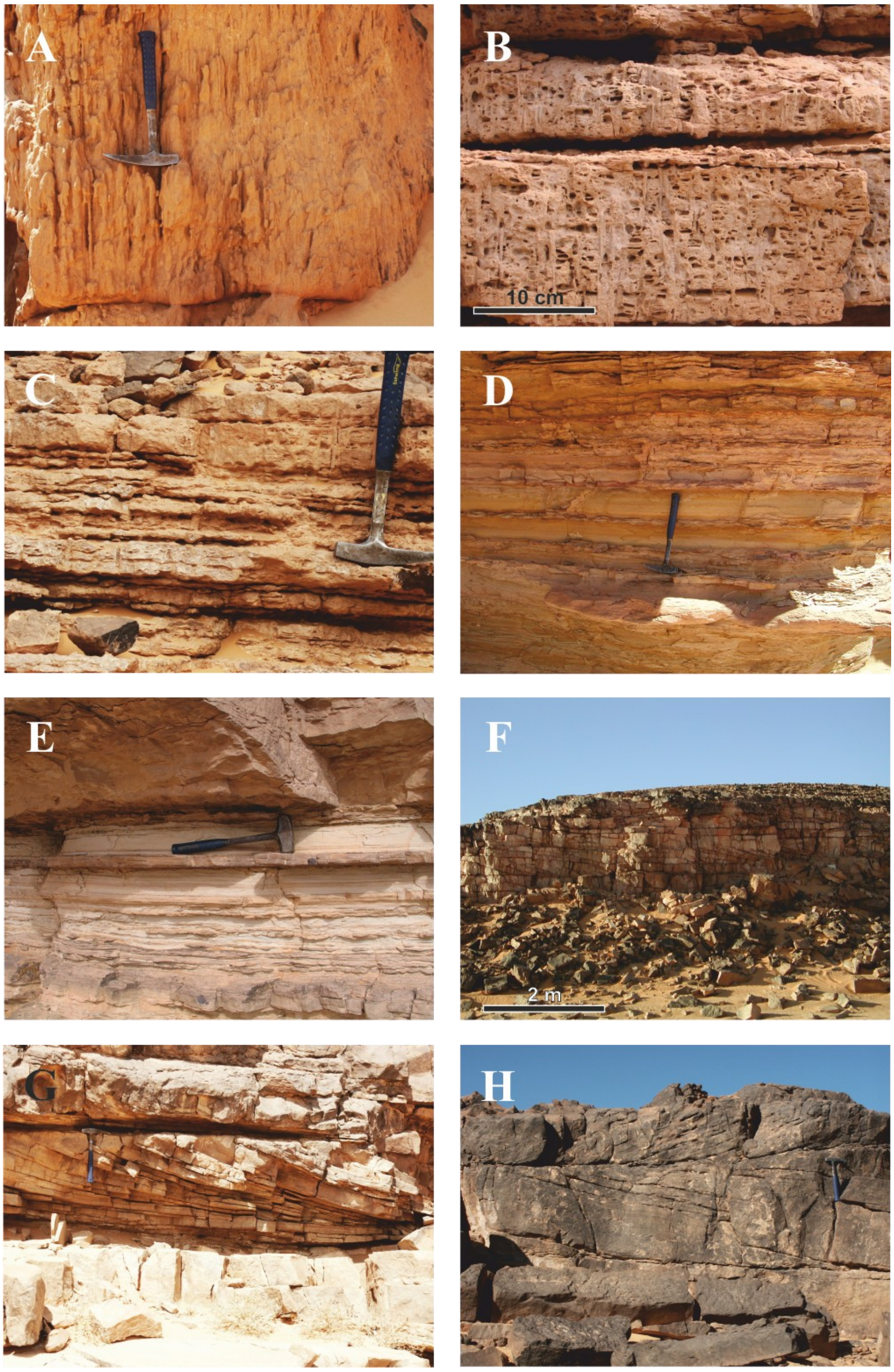


Figure 28.- Field view of some characteristicas facies of the Hawaz Formation in the western Gargaf area. **A** = Thick bedded, massive, medium- to coarse-grained sandstones intensively bioturbated by *Skolithos* (pipe rock); lower unit. **B** = Thinly stratified fine-grained sandstones intensively bioturbated by vertical burrows (*Skolithos*); lower unit. **C** = Thinly stratified fine-grained sandstones with scarce bioturbation; middle unit. **D, E** = Thinly stratified volcanic ash horizons (K-bentonite beds); middle unit. **F, G** = Large-scale sigmoidal cross-bedded sandstones; upper unit. **H** = Large-scale sigmoidal cross-bedded sandstones showing bidirectionality; upper unit.

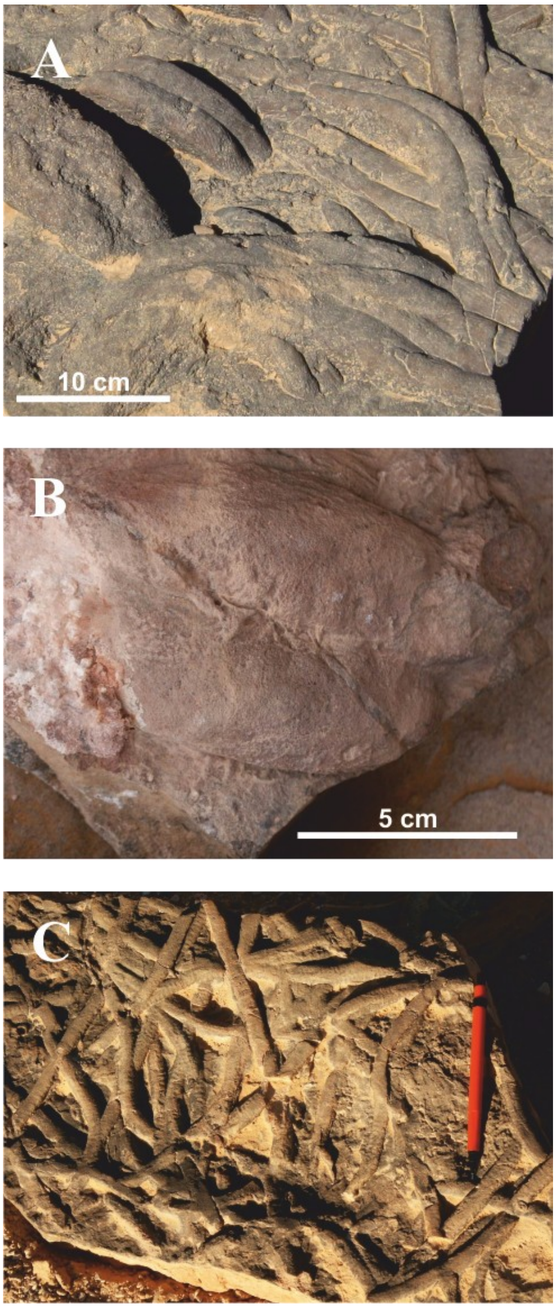


Figure 29.- Characteristics trace fossils from the Hawaz Formation. **A** = *Cruziana*. **B** = *Rusophycus*. **C** = *Artrophycus*.

includes scarce K-bentonite beds and/or graywackes made of a mixture of reworked sandstones and volcanic ash. The thick sandstone bodies of the upper unit generally exhibit low bioturbation. Gamma-ray of the upper unit have relatively homogeneous, low values except for some channelized bodies containing abundant clay chips and the thick, matrix-rich beds related to K-bentonites.

Palaeocurrents show two main trends (Fig. 24). Smaller-scale structures (ripples and small sigmoidal cross-bedded sets) show a wide dispersion. In contrast, larger-scale structures, which characterize the upper and lower parts of the Formation, display a paleocurrent trend towards the NE-NW and, locally, bidirectionality (Fig. 28.H).

There is no agreement regarding the age of the Hawaz Formation. The only available chronostratigraphic data on the Formation in the Murzuq Basin is provided by acritarchs and chitinozoans (Miles, 2001). According to this author, the top of the Hawaz Formation is no younger than Llandeillian, as defined by the presence of abundant *Acanthodiacrodium* sp., whereas the base is no older than Llarvirnian, as defined by the presence of *Villosacapsula irrorata* and *V. setosapellicula*. Thus, a Llanvirnian-Llandeilian age, following the traditional Ordovician British series, is assigned by this author to the Hawaz Formation. These series correlate with the late Darriwilian and the Sandbian of the global Ordovician subdivision. On the other hand, following the acritarch biohorizons proposal of Vecoli and Le Hérissé (2004) for the northern margin of Gondwana (which includes some Ordovician Libyan basins), the first appearance biohorizon of *Villosacapsula setosapellicula* corresponds with the boundary between the Middle and Late Or-

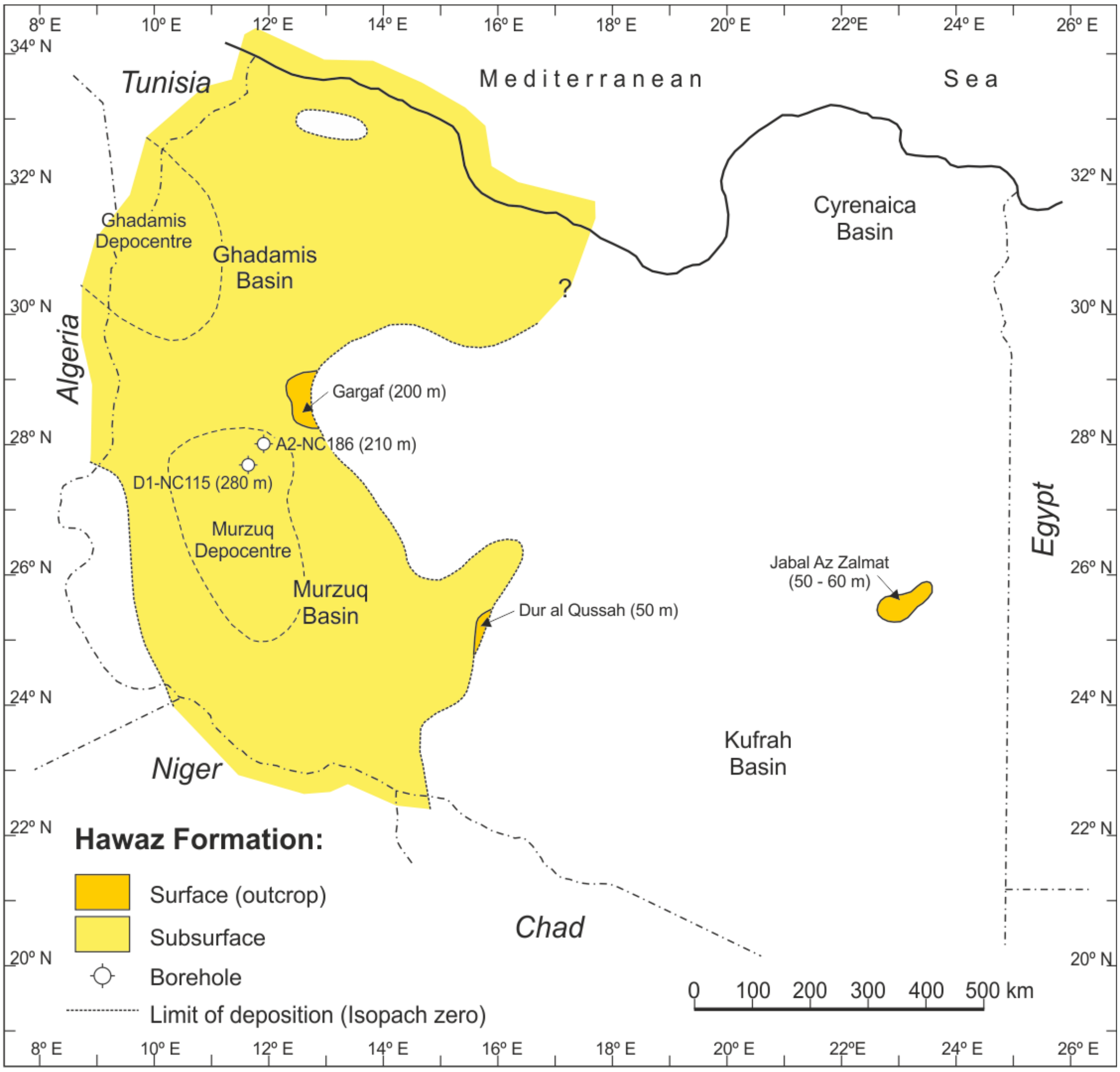


Figure 30.- Outcrop and subsurface extents of the Hawaz Formation in Libya. Modified from Hallett (2002).

dovician. Accordingly, a Middle Ordovician age, probably including the base of the Upper Ordovician, is proposed for the Hawaz Formation. However, in the neighboring Kufrah Basin, Seilacher et al. (2002) considered the Hawaz Formation as Arenigian (a British series that can be correlated with the Floian and Dapingian stages – Lower-Middle Ordovician – of the global Ordovician subdivision) based on the occurrence of certain ichnospecies of the trace fossil Cruziana.

Sedimentological analysis of the Hawaz Formation has been carried out by Ramos et al. (2006), which defined up to five facies associations. There are: subtidal sst.; storm-reworked, shoreface sst.; shoreface to beach sst.; channel sand bodies and nearshore to inner platform sst. The lower Hawaz unit is characterized by deposition in a nearshore to inner platform setting, grading upwards to shoreface to beach environments. The middle Hawaz unit recorded detrital deposition in a shallow marine environment where shoreface to beach, storm-reworked and minor tidal channel fill deposits appears interstratified with scarce volcanic ash beds. The upper Hawaz unit was deposited in a marine platform dominated by deposition of subtidal and tidal channel fill deposits, which appears interstratified with storm-reworked deposits and scarce volcanic ash beds. These facies assemblages result of the deposition in a large-scale, NNW to SSE oriented, estuarine environment, where differences between wave and tidal power and transgressive versus regressive setting are recorded.

The Hawaz Formation extent in the subsurface across the Murzuq Basin (Fig. 30), and crops out in the northern (Gargaf) and southeast (Tibesti) boundaries. In the Murzuq subsurface their thickness reach up to 210 m in block NC186 (Gil, 2013) or 280 m in block NC115 (Aziz, 2000), whreas towards the SE margin (Dur al Qussah) thickness is reduced to less than 50 m (Mamgain, 1980). This formation has been also recognized in the subsurface of the Ghadamis Basin and to a lesser extent, in the Az Zaimat mountains, north of the Kufrah Basin, where a 50-60 meters thick composite section has been proposed by Tawengi et al. (2012).

3.2.4. Melaz Suqran Formation:

The Melaz Suqran Formation was firstly introduced by Massa and Colomb (1960) after Jabal Melaz Suqran in the western Qargaf. Its usage was subsequently extended to the Ghat and Jebel Ben Ghanimah areas by Burollet (1960).

In its type area it constituted a 60 meters thick sequence largely mud-prone greenish grey in colour (Figs. 31, 32.A). Their basal boundary is a major erosion surface through which, it unconformably overlies the Hawaz Formation. Their upper boundary is another erosive unconformity under the Mamuniyat Formation (Fig. 32.A). In other areas, where Hawaz or Achabiyat forma-

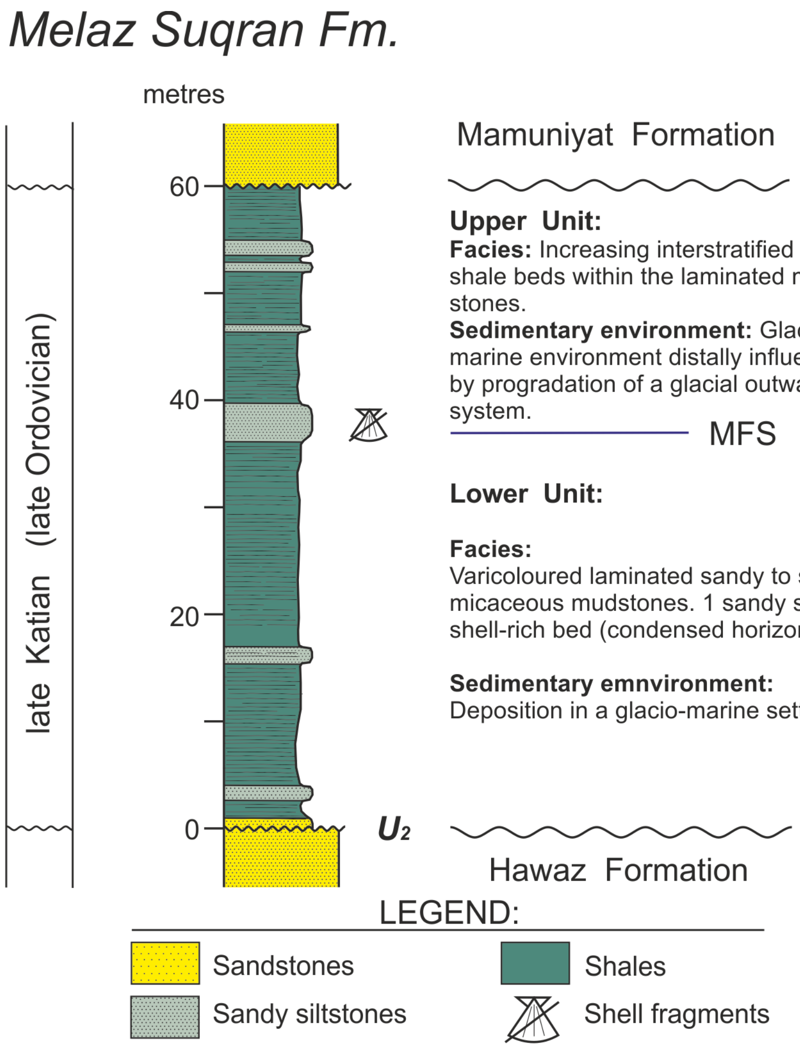


Figure 31.- Stratigraphic type section for the Melaz Suqran Formation at western Gargaf. Modified from Gundobin (1985).

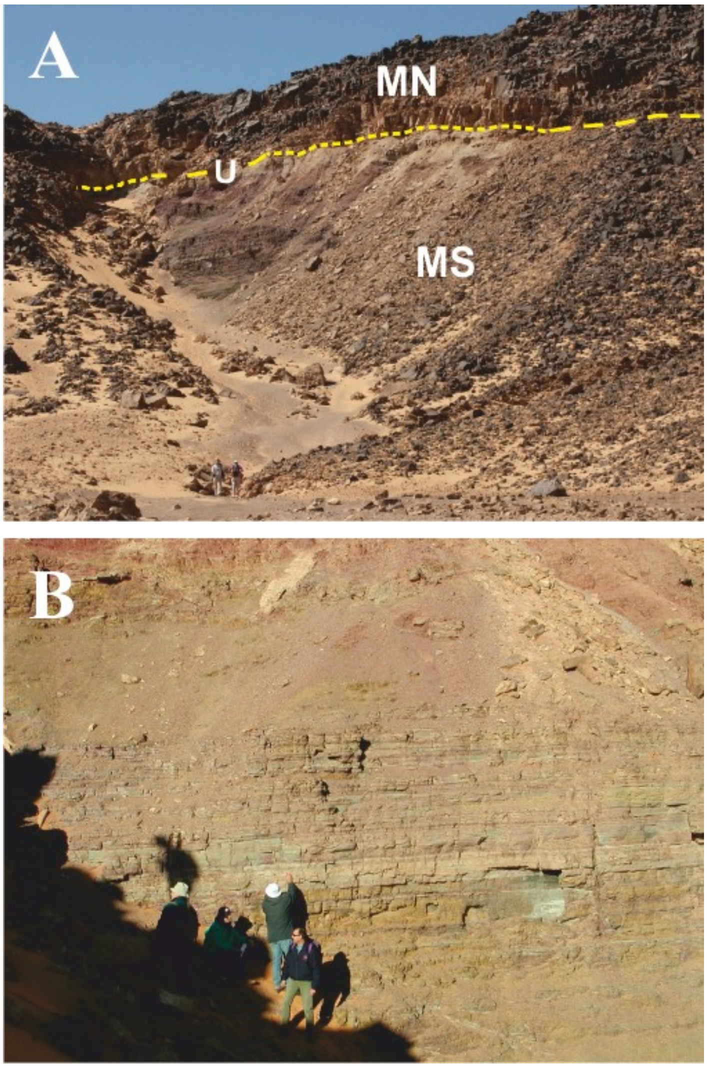


Figure 32.- **A**) Image showing the type section outcrop for the Melaz Suqran Formation in western Gargaf and their relationship with the overlying Mamuniyat Formation. **B**) Close-up view of the Melaz Suqran Formation at their type locality. **MN** = Mamuniyat Formation; **MS** = Melaz Suqran Formation. Surface U represent the basin-scale unconformity shown in Fig.19.

tions are not present (i.e. near Ghat), Radulovic (1985) and Grubic *et al.* (1991) also reported Melaz-Suqran Fm. directly overlying the Hasawnah Fm.

In the Ghat area, McDougall et al (2005) report a Melaz Suqran section up to 74 meters thick, and subdivided the Formation into two units called from oldest to youngest, MS1 and MS2 (and probably a third MS3 which is poorly exposed and at times may be misinterpreted due to fault block repetition of MS1). The lower MS1 forms the bulk (up to 56m thick) of the outcropping section in the Ghat area, and it is made up by greenish grey-colored, poorly sorted micaceous silty or sandy mudrock, with scattered pebble sized clasts. The upper MS2 is 5 to 10 m thick and made up by heterolithic sandstones with pervasive soft sediment deformation. In other areas, Collomb (1962) reported the presence of polished and striated boulders and cobbles of granite, gneiss and quartzite.

Figure 33.- Well rounded clast of very coarse-grained sandstone within the laminated micaceous mudstones of the lower Melaz Suqran Formation. The clast could be interpreted as a dropstone. Image from the Tahrmt area after McDougall et al. (2005).

In the western Gargaf type area, the Melaz Suqran Formation is lithologically constituted by very poorly sorted, silty or sandy, commonly micaceous mudstones and highly argillaceous sandstones which are varicoloured green, brown, red and grey, chloritic and thinly bedded (Fig. 32.A, B), containing scattered outsize clasts of different lithologies, which have been interpreted as dropstones. Most of these interpreted dropstones (Fig. 33) are well rounded clasts up to 5 cm in size, and may reflect a lengthy reworking. The Melaz Suqran Formation contains poorly preserved fragments of marine fossil remains. Collomb (1962) reported the presence of trace fossils as well as fragments of trilobites, bryozoa, brachiopods and graptolites which suggest a Llanvirnian-Llandeilian age. Based on the brachiopods content, Havlicek and Massa (1973) propose a Caradocian age for the Formation. Gundobin (1985) reported the presence of the brachiopod *Plectothyrella libyca* in the type section in western Gargaf, which is assumed to be of Ashgillian age. Across much of the western Gargaf type area, it crops out a shell-rich condensed horizon (MFS in Fig. 31) which has been interpreted as *"Hirnantian*" fauna (Ashgillian). Melaz Suqran Formation is rich in palynological remains, and based on subsurface samples derived fom block NC115, Miles (2001) propose an Early Ashgillian (Pusgillian) age according to the British series, that it means a Late Katian (Upper Ordovician) age according to the international marine series.

In the subsurface of the Murzuq Basin the Melaz Suqran Formation contains radioactive shales with high thorium content which are interbedded with minor siltstones and sandstones.

The Melaz Suqran Formation largely extents across most of Libya (Fig. 34). It has been reported from the subsurface of the Ghadamis and Cyrenaica basins, although it has not been reported from the Kufrah Basin. In the Murzuq Basin the Melaz Suqran Formation crops out extensively in all the basin borders: in the western Gargaf it reach up to the above mentioned 60 meters in thickness. It has also been mapped along the western and south western flanks of the Murzuq Basin, cropping out from south Ghat to Tikiumit, where it reach more than 70 meters in thickness (McDougall et al, 2005). In the western Dur al Qussah area the Formation is reduced to a thickness of 25 meters (Fig. 34). In the subsurface of the Murzuq Basin the Melaz Suqran Formation displays variable thicknesses; in well C1-NC 58 the thickness of this unit is 25m; in block NC115 the thickness ranges between 172 meters (well A1-NC115) to 45 meters (well E1-NC115), and it is absent in a number of boreholes (i.e.: G1, H6 or I1). The reduced thickness and local absence of the unit may be indicative of the effect of Caradocian tectonism in this area.

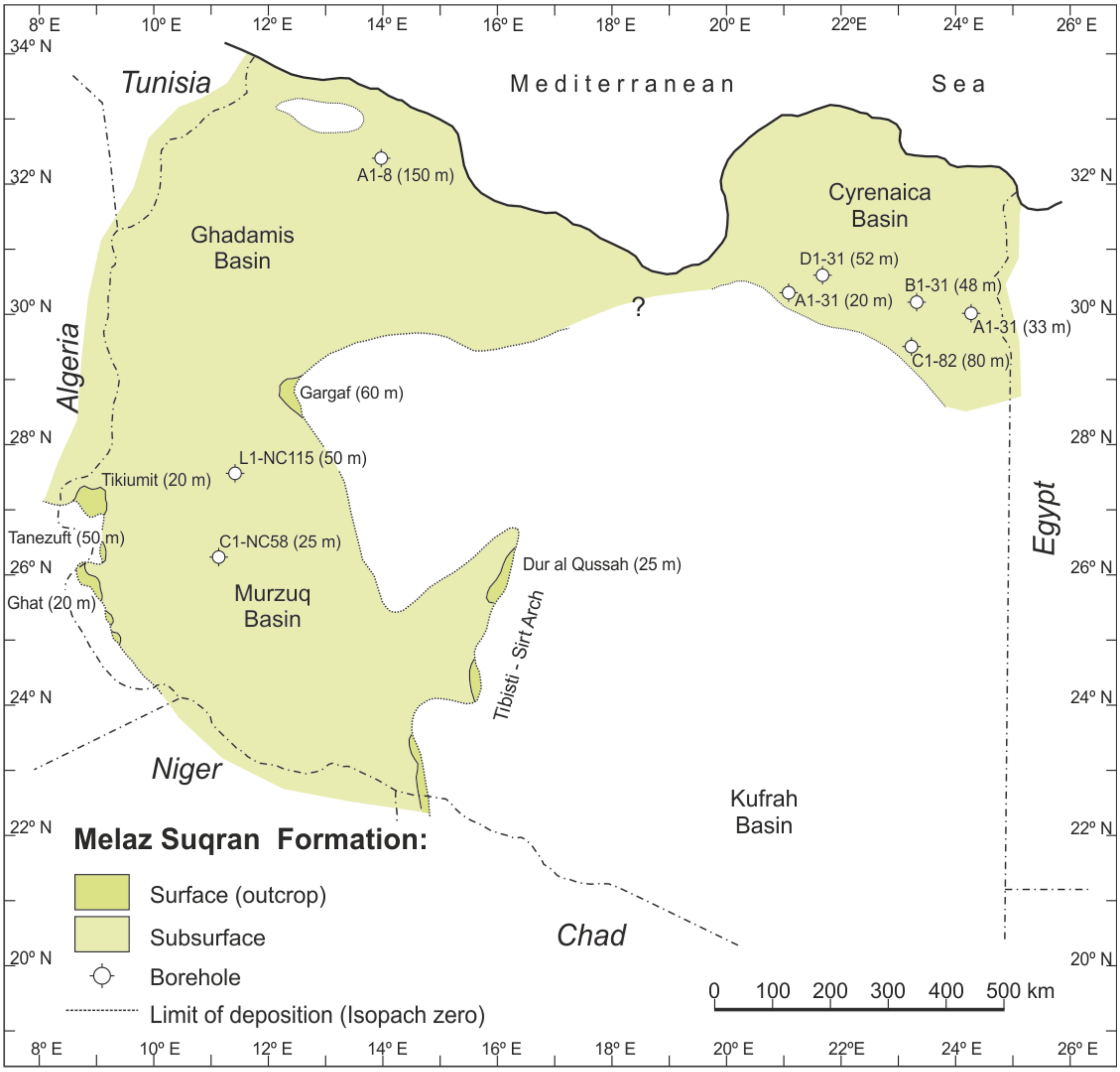


Figure 34.- Outcrop and subsurface extents of the Melaz Suqran Formation in Libya. Redraw from Hallett (2002).

The Melaz Suqran Formation represents a significant flooding event, where the maximum flooding surfaceis represented by the shell-rich condensed horizon (MFS in Fig. 31). On the basis of the presence of polished and striated exotic boulders and cobbles, Collomb (1962) suggests a periglacial environment and iceberg rafting. Blanpied et al (2000) described an association of large boulders and striated pebbles in a silty matrix, graded beds and large scale cross bedding in the Melaz Suqran Formation which they attributed to a proglacial delta. Outcropping on the western flank of the basin McDougall and Martin (2000) found an association of glacial and non glacial facies representing distal shelf and ice margin deposits. Finally, McDougall et al (2005) interpreted that, the lack of stratification, poor sorting, abundant de-watering structures and the presence of outsized, ocasionally exotic clasts within much of the Melaz Suqran Formation suggests deposition primarily within a glaciomarine setting, initially from a combination of dilute debris flows or iceberg melt out associated with discharge from a retreating tidewater glaciar. The upwards increase in interbedded sand and silt represented by Unit MS2 in the Ghat area implies a rapid progradation of the glacial outwash system. However, the fine grain size suggests deposition from distal density flows on a steep gradient in relatively deep water. Coarser grain sands and gravel were most likely trapped in the ice proximal environment and have not so far been observed. The brachiopods fossils also indicate a cold water environment.

3.2.5. Mamuniyat Formation

The Mamuniyat Formation was first defined by Massa and Collomb (1960) in the western Gargaf, where a section 90 to 140 m thick crops out; later, a type section about 120 m thick was proposed by Parizek et al. (1984) in the Idri area. The Mamuniyat Formation fills the palaeorelief related to the above exposed late Ordovician glaciation, and consequently it typically displays extremely variable thickness variations. In short, the Mamuniyat Formation could be defined as a sand package occurring between two muddy units: the argillaceous Melaz Suqran at bottom and the Tanezzuft shales at top. It contain rare and fragmentary pelecypods and brachiopods, the brachiopod fauna suggests a periglacial environment. There are two capital works centred on the study of the Mamuniyat outcrops; the first one focuses on the western Gargaf (Deinoux et al, 2000) and the second one in Gath zone (McDougall et al, 2005). Internally, the Mamuniyat Formation records several erosive surfaces recording successive incision and infill cycles. According to McDougall et al (2005), in the Gath area the Mamuniyat Formation could be divided into three units (Fig. 35); a lower (LM), middle (MM) and upper (UM) units; in turn, the lower Mamuniyat can be divided into two sub units (LM1 and LM2), and the upper unit in three subunits (UM1, UM2 and UM3). All the units and subunits are separated by erosional surfaces. The lower Mamuniyat boundary varies from strongly erosive in the centre of the palaeovalleys to disconformable on the intervening highs. Accordingly, the Lower Mamuniyat may truncate the entire Melaz Suqran Formation and rest on the Hawaz Formation (Figs. 25, 36.A). Towards the SW, in the Tihemboka high, the lower boundary with the Melaz Suqran Formation seems to be locally transitional, whereas in the eastern part this lower boundary is a basal ferruginous sandstone bed passing laterally into a hematite crust, reflecting a major hiatus (Klitzsch, 1966). The upper boundary of the Mamuniyat Formation is also an erosion surface.

The entire Lower Mamuniyat is a sand prone unit which can be subdivided into two sub units, termed (from oldest to youngest), LM1 and LM2 separated by a locally extensive striated pavement. The lowermost LM1 is largely confined to lows within the palaeovalleys. In the Ghat zone it is well-exposed to the South of Ghat and the Tahrmt area, where it reach up to 25m in thickness. It is made up by thick-bedded, fine grained sandstones forming multistorey and multilateral channel bodies (Fig. 36.B) truncated by a major striated pavement of glacial origin. The LM2 subunit has thicknesses ranging from only several metres on the highs to at least 50 metres in the palaeovalleys. It comprises silty sandstones in the base grading upwards into fine-grained sand sheets with ripples and occasional crawling traces. The LM2 subunit roughly constitutes a fining-upwards sequence.

The Middle Mamuniyat (MM) is a thin, mud prone unit forming a roughly coarsening-upwards sequence (Fig. 35). In the western Gargaf, the base of

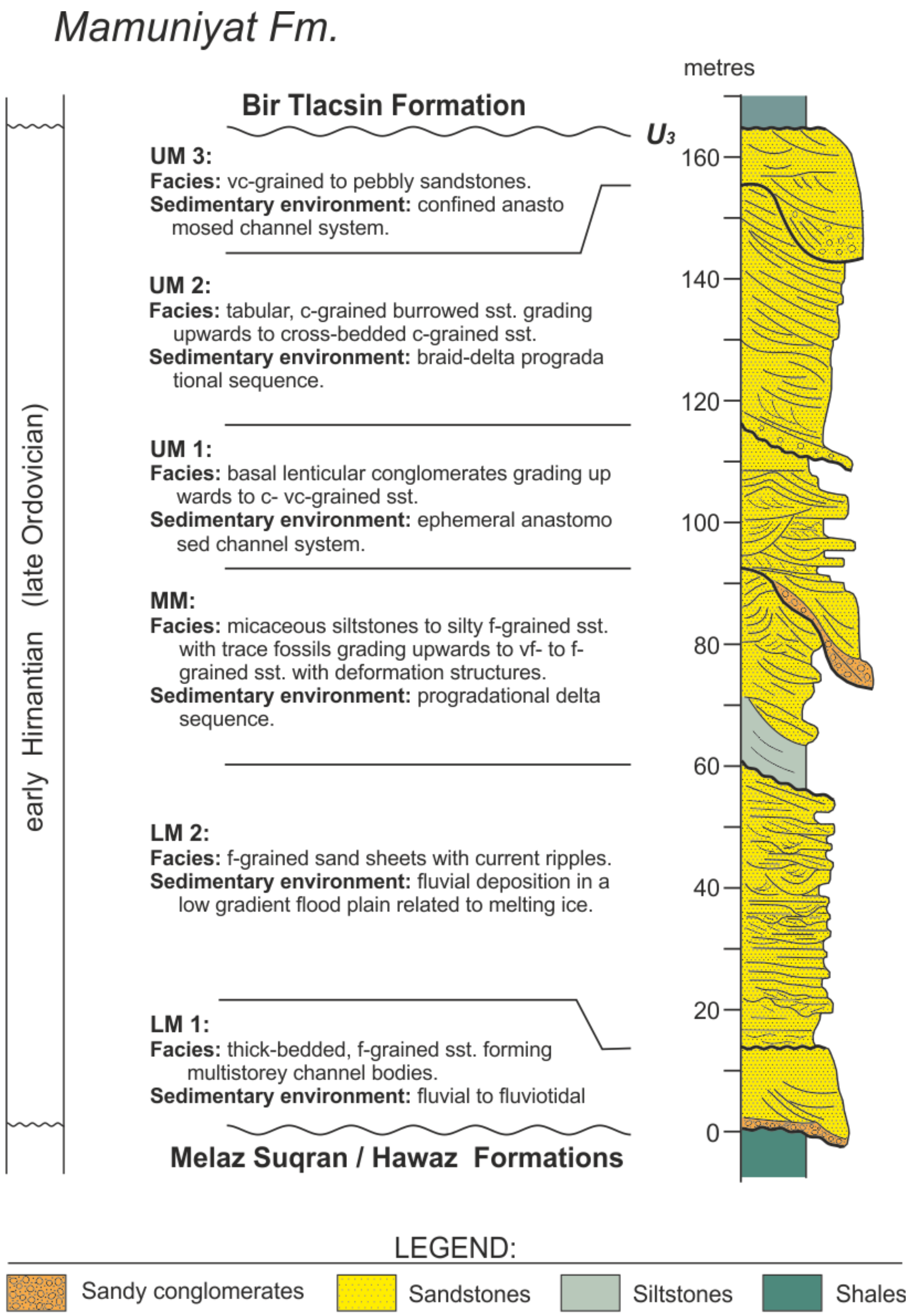


Figure 35.- Stratigraphic type section for the Mamuniyat Formation in the Ghat zone. Modified from McDougall et al (2005). Surface U_3 represents the basin-scale unconformity shown in Fig.19.

the MM is a major regional unconformity associated with glacial erosion which locally removes a part of the Lower Mamuniyat (Deinoux et al, 2000). In the Ghat zone the Middle Mamuniyat is poorly exposed, and their outcrops are incomplete due to truncation by the overlying Upper Mamuniyat (McDougall et al, (2005), which locally could erode the whole of the MM unit (Fig. 37.A). The thickness of the Middle Mamuniyat ranges from less than 10 m to more than 25 m. The Middle Mamuniyat consist of highly micaceous sandy siltstones, silty sandstones and fine grained argillaceous sandstones grading upwards to thickly-bedded, very fine- to fine-grained sandstones hosting deformation structures (Fig. 37.B). Cores from the subsurface of the Murzuq Basin show as the fine grained sandstones of the Middle Mamuniyat Formation have frequent vertical burrows, mainly *Skolithos* and *Monocraterion*, and occasionally horizontal traces as *Palaeophycus* and *Zoophycus.*

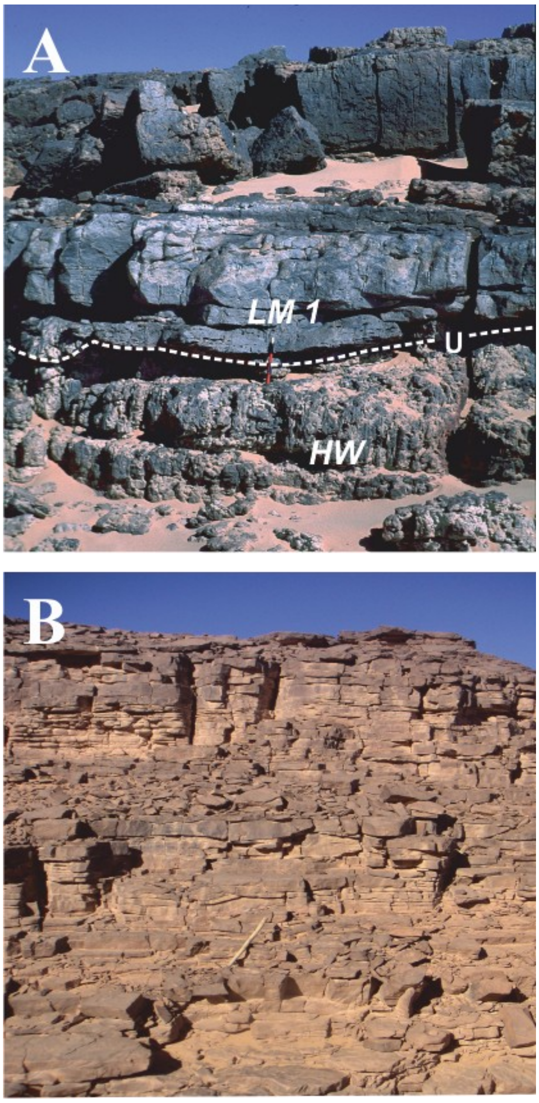


Figure 36.- A) Lower boundary of the Mamuniyat Formation in the Ghat area. In this point, the lower Mamuniyat unit (LM1) overlies the Hawaz Fm (HW) by means of an erosive glacial surface (U_2). See also Fig. 25. **B)** Field image of the characteristics sheet-bedded sandstones of the LM2 subunit.

The Upper Mamuniyat unit is a sandy unit which can be subdivided into three sub units, termed (from oldest to youngest), UM1, UM2 and UM3 separated by erosional surfaces that locally could erase some of them. As such, a thickness for the unit is not clearly valuable. McDougall et al. (2005) consider a minimum thickness of 60 m for the Upper Mamuniyat in the Ghat area. The UM1 subunit mainly developed in the palaeovalleys, where it reaches 10 to 20 m in thickness. Their basal boundary is a major erosion surface. UM1 mainly comprises lenticular conglomerate beds containing mudchips, overlain by coarse- to very coarse-grained, poorly sorted pebbly sandstones. Locally, at top, thin bedded (1-2m thick), rippled intervals occur. The UM2 subunit is the thickest and most widespread of the 3 sub-units occurring across much of the Ghat zone. However, it is best developed in the palaeovalleys, where their thickness reach up to 42 m. In contrast to the underlying UM1 subunit, the UM2 has a broadly tabular aspect. This subunit is typically made up by a basal interval of tabular beds of poorly sorted, slightly argillaceous, coarse-grained bioturbated sandstones (Fig. 37.C) containing trace fossils as *Planolites, Thalassionoides, Phycodes* and *Cruziana*. This basal interval grades upwards to a tabular bedded interval made of clean cross-bedded sandstones (Fig. 37.D), forming a broadly coarsening-upwards sequence. The UM3 subunit mostly occurs in the deeply incised palaeovalleys eroding the UM2 and UM1 subunits. Their basal erosion surface is steep-sided and highly irregular with a relief of up to 30m although the infill does not exceed 12 m in thickness. It consists in very coarse grained, poorly sorted, pebbly sandstones.

Palynological remains have been provided from wells in block NC115. According to this, Miles (2001) suggest that the presence of *Rhabdochitina magna*, *Jenkinochitina lepta* and *Tanuchitina elon-*

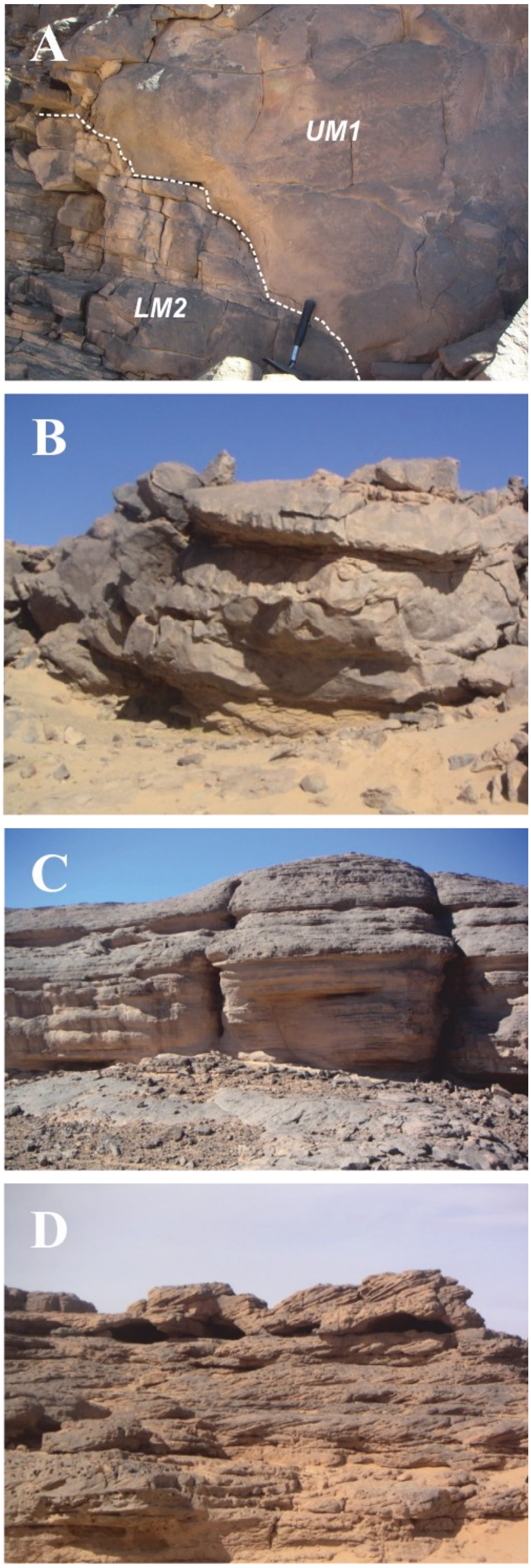


Figure 37.- A) The lower boundary of the Upper Mamuniyat unit (UM1) is an erosive surface which locally could erode the entire Middle Mamuniyat unit, setting out the UM unit directly on the Lower Mamuniyat (LM2). **B)** Image showing sand balls in the top of the Middle Mamuniyat unit. The photo was taken in the Ghat area. **C)** Tabular sandstones of the UM2 subunit. **D)** Cross-bedded sandstones typical of the upper part of the UM2 subunit.

gata suggest a Hirnantian – Cautleyan age, but the absence of *Ancyrochitina merga*, indeed of the genus *Ancyrochitina*, strongly suggests a Hirnantian age for the Mamuniyat Formation.

The Mamuniyat Formation largely extents across most of Libya (Fig. 38). It is present in the subsurface of the Murzuq, Ghadamis Kufrah and Cyrenaica basins. In the Murzuq Basin the Mamuniyat Formation crops out extensively in all the basin borders. In the western Gargaf, were it has been mapped by Deynoux et al (2000), it reaches up to 120 meters in thickness. The Mamuniyat Formation has also been mapped in the Ghat zone (western limit of the Basin) by (McDougall et al, 2005), wich reported thicknesses ranging between 130 and 165 metres. Outcrops of the Mamuniyat Formation have been also reported from the Dur al Qussah and Mourizidie regions (Fig. 38). In the subsurface of the Murzuq Basin the Mamuniyat Formation displays very variable thicknesses, but a depocenter up to near 300 m thick seem to be defined.

As a whole, the sand prone Mamuniyat Formation represent detrital deposition in a glacially influenced environment, where glacial erosion surfaces are the responsible of the Mamuniyat subdivision. According to McDougall et al (2005), the Lower Mamuniyat unit (LM) records, in their lower (LM1) part, deposition in a fluvial to fluviotidal environment subject to a degree of tidal reworking. The soft deformation notated in this subunit, which increases upward, is interpreted as the result of glaciotectonism associated with the ice advance recorded by the striated erosion surface on the top of the LM1 subunit. Palaeocurrent data suggests a source located eastwards. Towards their upper part (LM2), the unit records an environmental change to fluvial deposition developed within a sheet-flood dominated low gradient flood plain, probably fed by melting ice. The presence of bioturbation at the top of this subunit could be interpreted as a return of marine influence. The coarsening- and thickening-upwards sequence which constitutes the Middle Mamuniyat (MM) unit is interpreted as the result of the progradation of a delta system, where the fine-grained lower part of the MM records deposition in a distal mouth bar setting, whereas the coarse-grained with widespread soft-sediment deformation structures records high rates of sand accumulation within a proximal mouth bar to delta front environment. The Upper Mamuniyat (UM) unit records infilling of the large-scale palaeovalley system. The base of the UM is an erosion surface deeply incised within the older Mamuniyat strata Melaz Suqran and Hawaz formations, which could be related to ice movement or to catastrophic outflows caused by rapid ice retreat, ice dam failure or breach of moraines (McDougall et al, 2005). Other authors (Le Heron et al, 2004) suggest a subglacial origin for these palaeovalleys. The sands and gravels displaying large-scale trough cross-bedding of the UM1 records deposition in low relief bars belonging to an ephemeral anastomosed channel system characterised by transient high flow velocities. UM2 subunit records deposition on an erosional surface, were the basal conglomeratic lag infill the depositional lows. The bulk of the UM2 records the progradation of a braid-delta system, were the lower burrowed sandstones were deposited in a shallow marine environment dominated by density flows and storm currents, whereas the rest of the coarse-grained sandstones, displaying bipolar palaeocurrent patterns are interpreted as deposited in a tidally-influenced braid-delta front environment. Rocks of the UM3 subunit suggest an episode of canyon cut and infill, forming a confined, anastomosed channel system in response to glacial outburst floods. Deposition of UM3 may represent waning flow deposition from a single catastrophic event or several linked events.

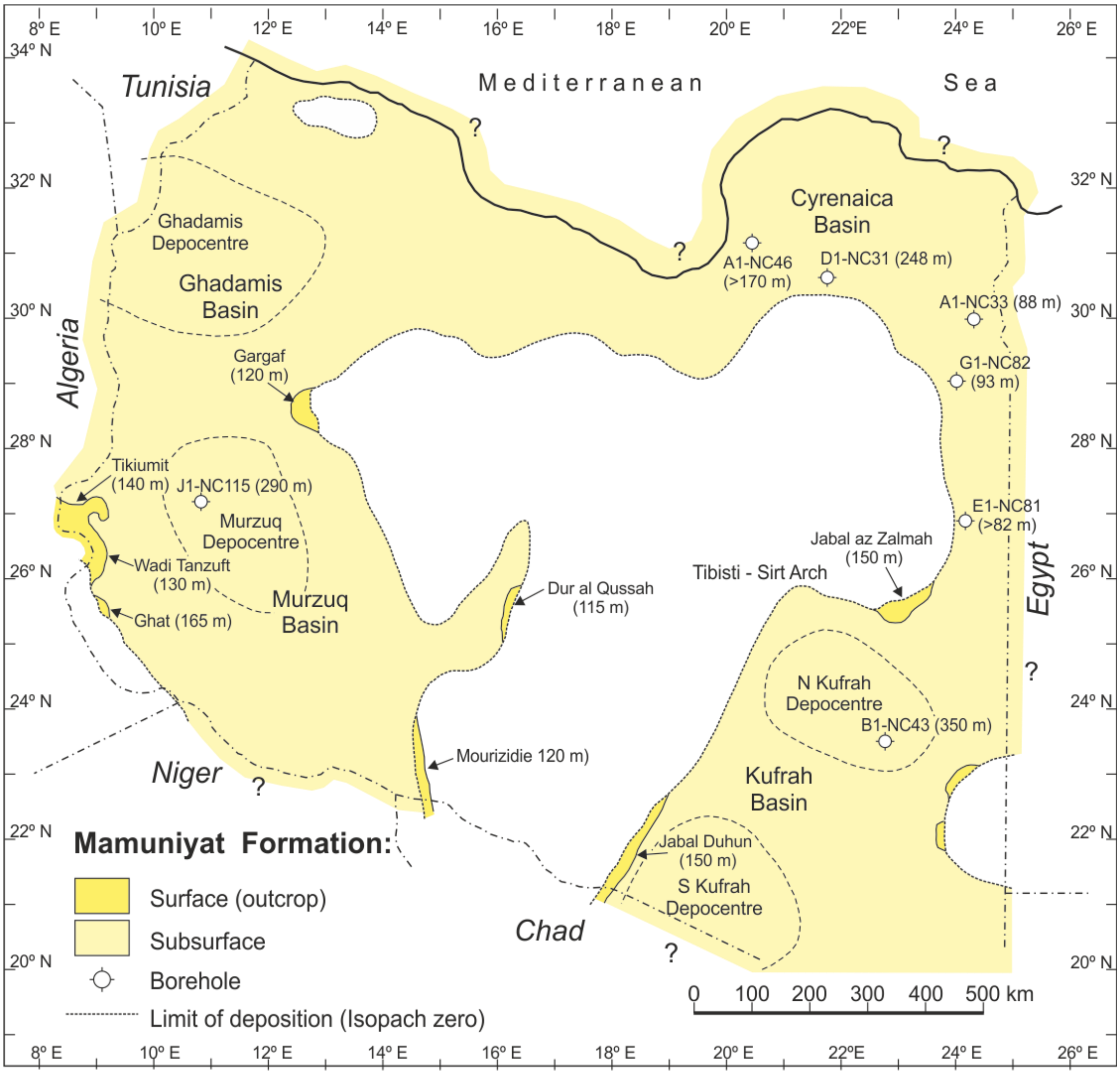


Figure 38.- Outcrop and subsurface extents of the Mamuniyat Formation in Libya. Redraw from Hallett (2002).

The Mamuniyat Formation is a major oil reservoir in the Murzuq Basin, and contains large reserves in concessions NC 101, NC 115 and NC 174 on the northern edge of the Basin. The oil is reservoired in the upper units of the formation including the channel fill sequence and the periglacial strata. In all of these areas the Mamuniyat Formation is in direct contact with the overlying Silurian source rock. Oil has not been found in areas where the Bir Tlakshin Formation intervenes between these two formations. In wells A1 and B1-NC 58 the upper part of the Mamuniyat Formation is intensely silicified.

The periglacial deposits of the Mamuniyat Formation also form part of the oil reservoir in southern Tunisia and Algeria.

3.2.6. Bir Tlacsin Formation

The Bir Tlacsin Formation has been not defined as a formal unit and it not appear in the lithostratigraphic lexicon of Libya (Mamgain, 1980). It was firstly defined in the subsurface of the area of the same name (A1-70) in Ghadamis Basin, where it is well developed. Probably it will be equivalent to the Iyadhar Formation, and many authors consider that this unit could be equivalent to the "Argiles microconglomeratique" from Souther Tunisia and Algeria. The Bir Tlacsin Formation has been correlated throughout the Ghadames Basin (Echikh, 1992), and several wells drilling the Murzuq Basin found, interstratified between the Mamuniyat and Tanezzuft formations, thin sequences attributed to the Bir Tlacsin Formation. It is well developed in the subsurface of blocks NC58, NC101, NC115, NC151 and NC186, but it is poorly exposed in surface outcrops. McDougall et al (2005) reported Bir Tlacsin sequences few meters thick cropping out near Ghat. The unit has been also reported from outcrops in western Gargaf.

The Bir Tlacsin Formation is a mud-prone unit which represents a transition between the Mamuniyat sandstones and the Tanezzuft shales. In the subsurface, where the Bir Tlacsin succession reach their maximum thickness, the formation consists of greywackes and black shales, often containing floating coarse sand grains, granules and pebbles (Fig. 39). McDougall et al (2005) defined the Bir Tlacsin Formation cropping out in the Ghat zone as a broadly coarsening-up thin sequence, composed of interbedded mud and silt or fine-grained sandstone (Fig. 40). In this zone, the top of the formation is marked by a 5 cm thick, iron-rich burrowed sandstone lag forming a hard ground and directly overlain by the Tanezzuft shales. The unit unconformably overlies the Mamuniyat Formation, and in turn, it is unconformably overlied by the Tanezzuft Formation which truncates the Bir Tlacsin Formation. The Bir Tlacsin Formation has a patchy distribution. Thickness varies rapidly, and variations suggest that this unit fills the irregular palaeotopography capping the Mamuniyat Formation, which was mainly caused by erosion related to the late Ordovician glaciation. The maximum thicknesses correspond with the palaeovalleys lows, and sequences thin or disappears over topographic highs. In the Murzuq Basin the thickest Bir Tlacsin sequence is found in well D1-NC115 were it reaches up to 130 m thick.

As the Bir Tlacsin Formation is mainly a unit developed in subsurface, it could be of interest to define their electric properties. Their typical log response is illustrated in Fig. 41. The top of the unit is easily identifiable at the base of the Tanezzuft hot shale zone. The base may be difficult to clearly distinguish from the Mamuniyat Formation, particularly close to paleohighs where the basal shales are silty or sandy. However, the impermeable Bir Tlacsin shales, with low separation between shallow and deep resistivities, provide a good criterion for distinguishing it from the underlying Mamuniyat permeable sandstones.

The age of the Bir Tlacsin Formation is uncertain and may vary locally. No age diagnostic fossils have been recorded from the formation in the Murzuq Basin. On the basis of the palynological assemblages provided by wells from block NC115, Miles (2001) reported that deposition of the Hirnantian Shale (equivalent to the Bir Tlacsin Formation) is also confined to the upper part of the Ashgillian (Hirnantian). These finds are in agreement with the strati-

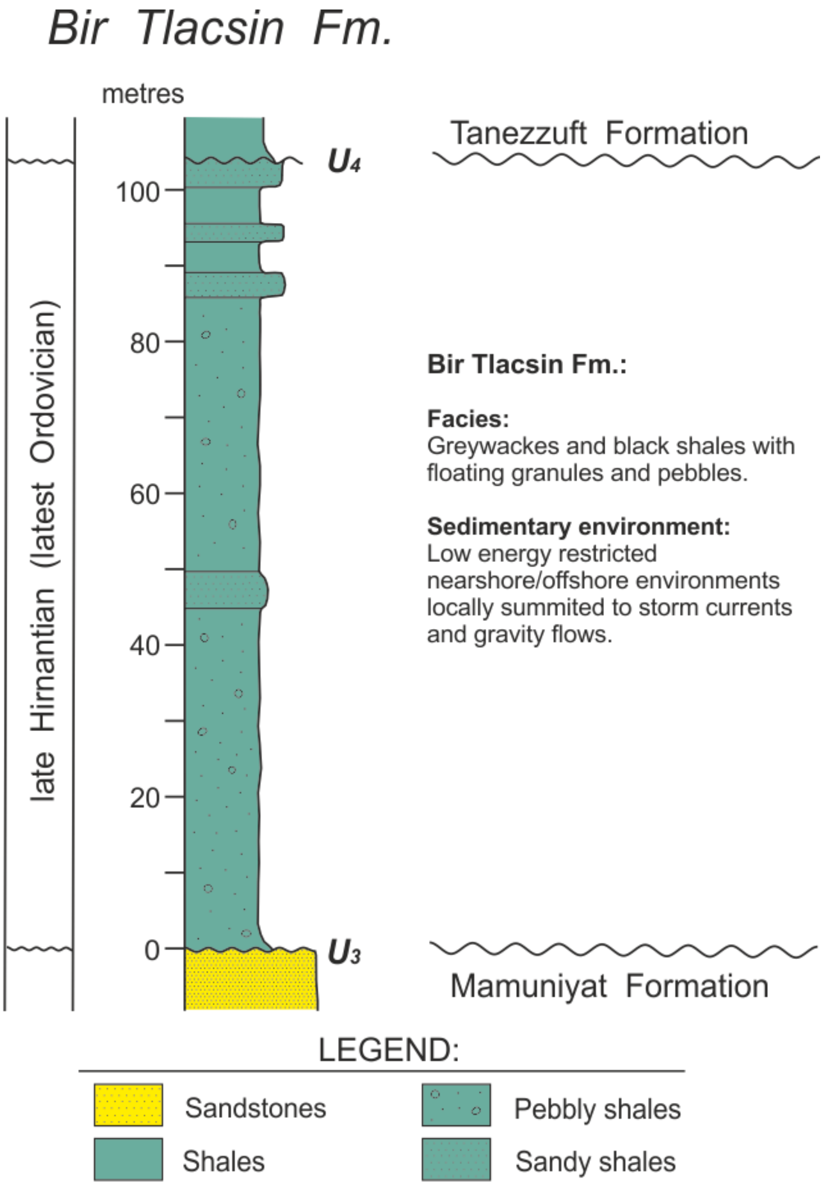


Figure 39.- Idealized lithological log for the Bir Tlacsin Formation in the subsurface of the Murzuq Basin. U_3 and U_4 are basin-scale unconformities shown in Fig.19.

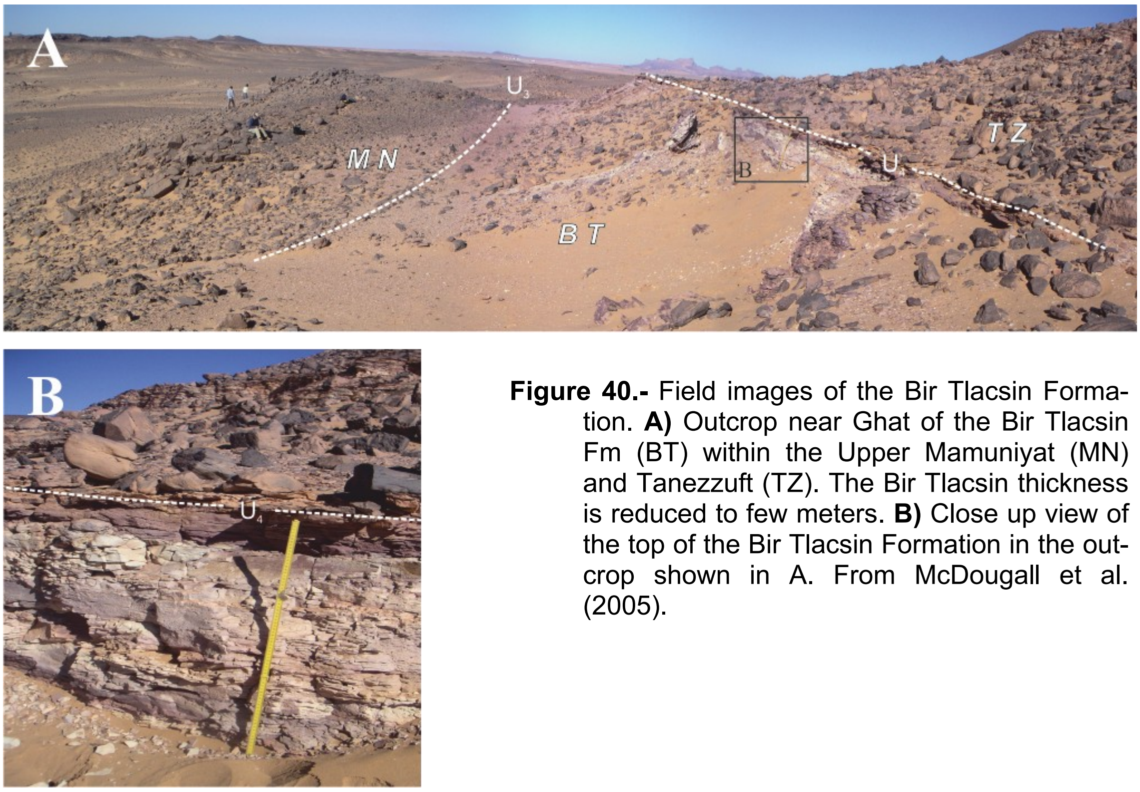


Figure 40.- Field images of the Bir Tlacsin Formation. **A)** Outcrop near Ghat of the Bir Tlacsin Fm (BT) within the Upper Mamuniyat (MN) and Tanezzuft (TZ). The Bir Tlacsin thickness is reduced to few meters. **B)** Close up view of the top of the Bir Tlacsin Formation in the outcrop shown in A. From McDougall et al. (2005).

graphic position of the Bir Tlacsin Formation within the underlying Mamuniyat and the overlying Tanezzuft formations.

The core interpretation of the Bir Tlacsin Formation suggest that the unit was originated as debris flow deposits (Echikh and Sola, 2000; Hallet, 2002) in marine palaeoenvironments varying from very proximal to distal (Miles, 2001). However, many authors are in disagreement with this interpretation. For example, Blanpied et al (2000) consider the Bir Tlacsin Formation (which laterally correlates with the Upper Mamuniyat) as wave dominated shoreface deposits accumulated during the basal Silurian transgression. Based on the study of outcrops of the Ghat area, McDougall et al (2005) defined the Bir Tlacsin strata as the result of either, aggradational or progradational deposition in a low energy protected nearshore or offshore environments swept by storm currents or possibly even sediment gravity flows during a high relative sea level. The common, although not ubiquitous, occurrence of soft sediment deformation is interpreted as high sediment supply.

The above mentioned thickness variations of the Bir Tlacsin Formation in subsurface, filling former palaeovalleys on the Mamuniyat Formation, could be highlighted by means of correlation panels. Figure 42 shows a SW-NE geological cross-section across the Murzuq Basin where an erosion surface on top of the Mamuniyat Formation originated a 450 km wide and 70 m deep paleovalley which was filled by Bir Tlacsin Formation. The presence of The Bir Tlacsin Formation in subsurface is an important feature from a petroleum point of view

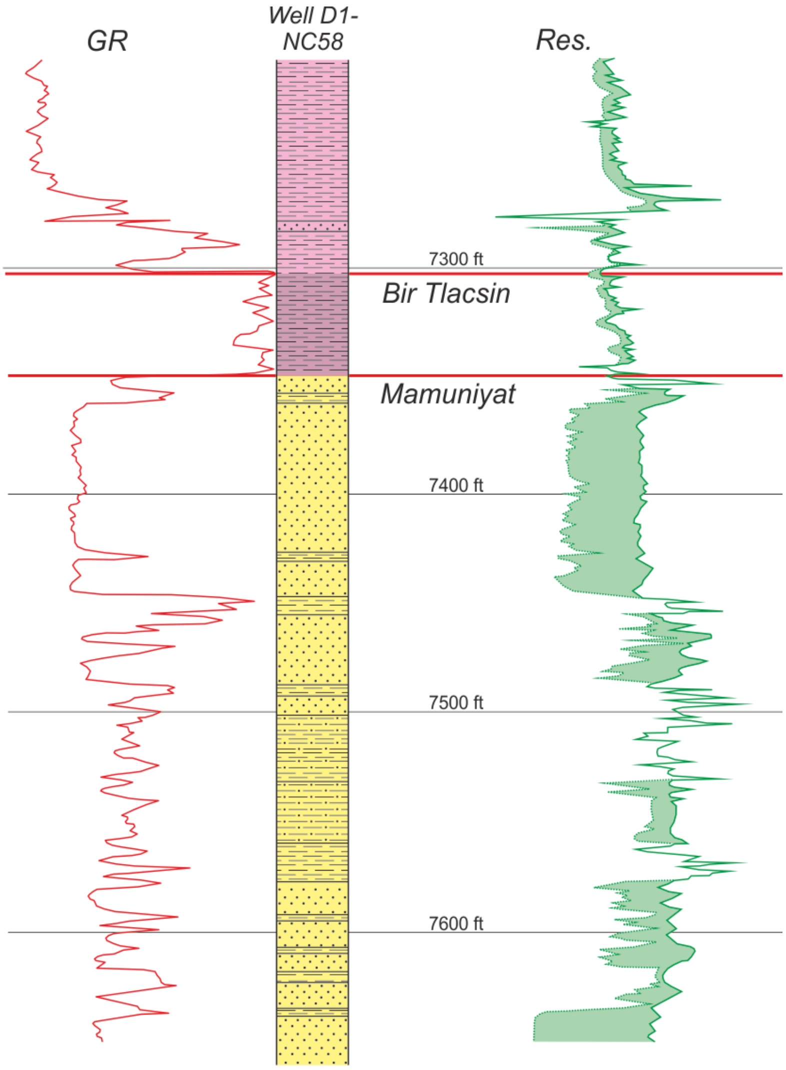


Figure 41.- Lithological and Gamma-Ray log of well D1-NC58 showing the GR response of the Bir Tlacsin Formation. Redraw from Echikh and Sola (2000).

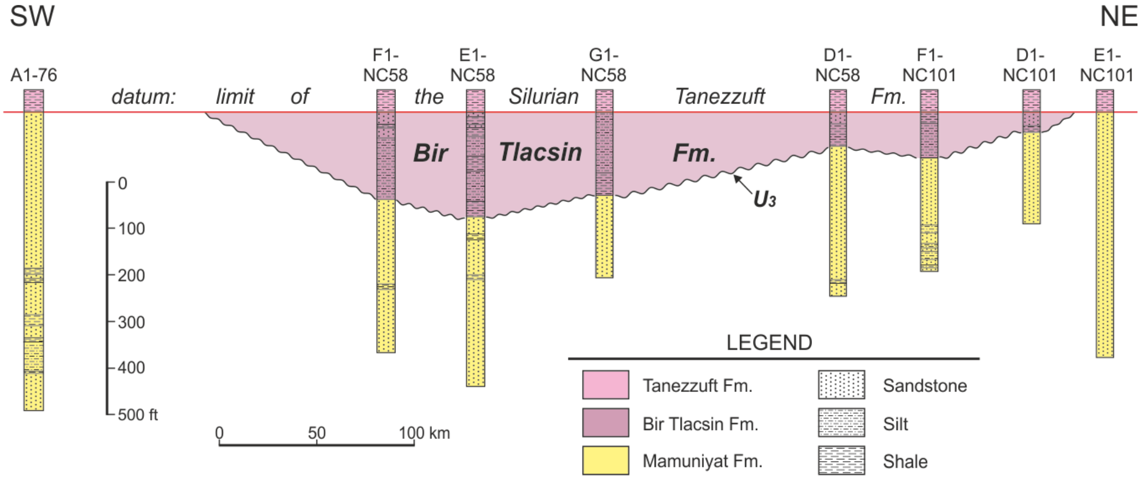


Figure 42.- SW-NE cross-section across the Murzuq Basin showing the large-scale geometry in the sursurface of the Bir Tlacsin Formation. See location of the cross-section in figure 43. Redraw from Echikh and Sola (2000). Surface U_3 represent the basin-scale

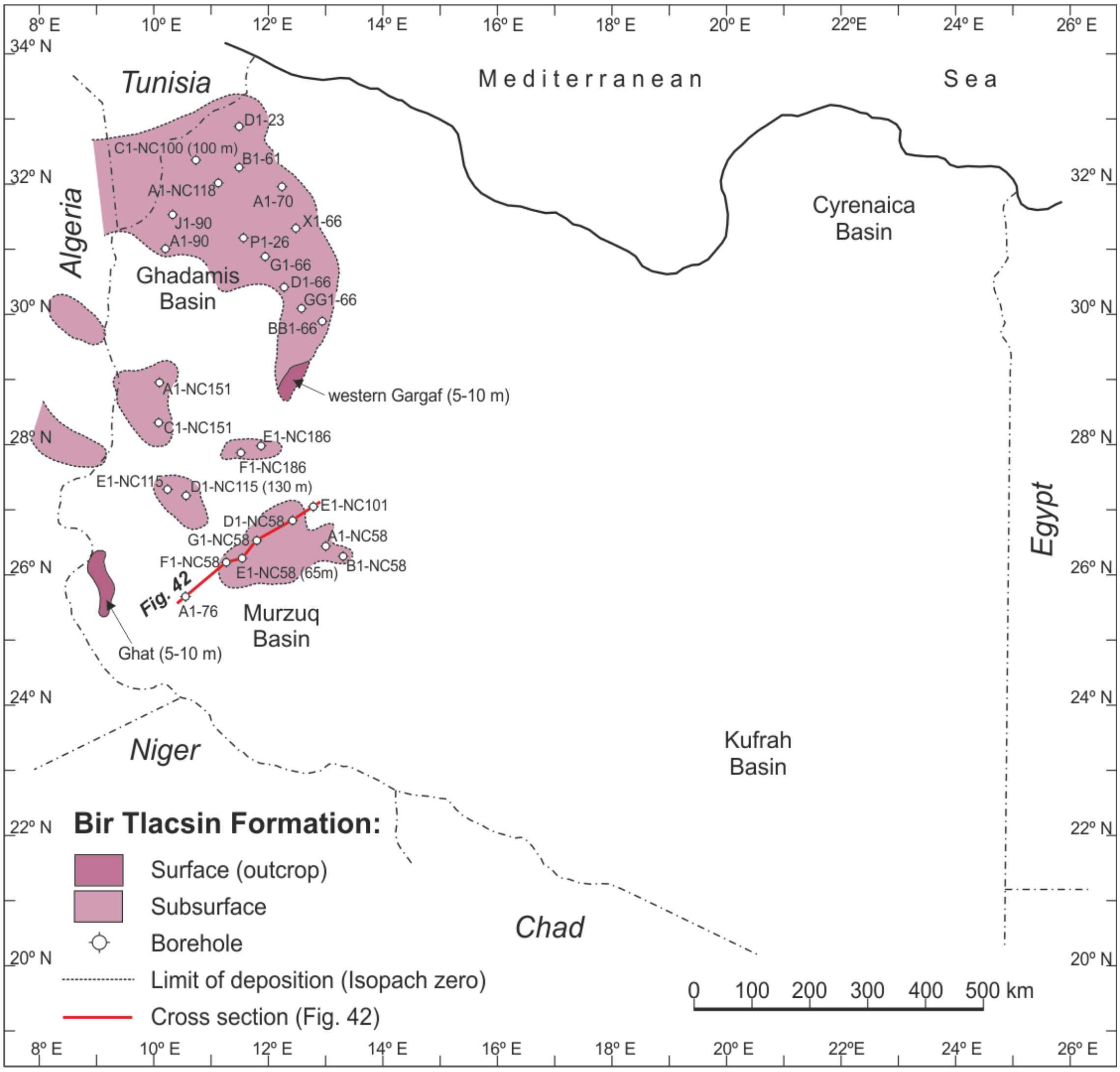


Figure 43.- Outcrop and subsurface extents of the Bir Tlacsin Formation in Libya. Modified from Hallett (2002).

(Echikh and Sola, 2000; Hallet, 2002), as it controlled the hydrocarbon accumulation potential of underlying reservoir rocks, since it forms a barrier between the Mamuniyat reservoir and the Tanezzuft source rocks.

The areal extent of the Bir Tlacsin Formation is limited to the western Libya (Fig. 43). It is present in the subsurface of the Ghadamis and Murzuq basins and also is sparsely present in thin sequences cropping in the Ghat and western Gargaf zones. The Bir Tlacsin Formation has not been reported from the Cyrenaica nor Kufrah basins.

3.2.7. Tanezzuft Formation

The Tanzzuft Formation was first defined in the former works by Desio (1936) from Wadi Tanezzuft, about 65 km north of Ghat on the western margin of the Murzuq Basin. In this location the basal boundary of the unit is not exposed, and Desio did not define the top of the formation, because this, Klitzslch (1965) established a para stratototype section 35km south of Ghat, where a complete section is present (Fig. 44). At this location the Tanezzuft Formation comprises 370 meters of dark grey marine graptolitic shales with thin siltstone and sandstone stringers in their lower part. The contact with the underlying Mamuniyat formation is unconformable, and is marked by a thin bed of ferruginous sandstone or a conglomeratic lag deposit (Fig. 45). The transition into the overlying Akakus Formation is gradual (Fig. 46). On the basis of well-log correlations, Abugares and Ramaekers (1993) suggested that multiple unconformities are present within the Tanezzuft Formation. The Tanezzuft Formation is composed of the Tanezzuft Shale and the Hot Shale member occurring locally at the base (Fig. 44). A regional facies change is observed in the Tanezzuft Formation of the Murzuq Basin. The sand content of the formation changes laterally, becoming more sandy towards the Brak-Bin Ghanimah Uplift, and towards the south of the basin where the sand content reaches up to the 20%. An isolith map (Fig. 47) of the sand percentage of the unit indicates an increasing in coarse clastic content towards the SE and SSW, suggesting active clastic inputs from these areas during deposition of Tanezzuft Formation times. The Tanezzuft Formation could be considered equivalent to the Lyadar Formation.

Lithologically, the Tanezzuft Formation mainly consists of light grey to brown and dark grey micaceous siltstones with interbedded minor siltstones and fine-grained sandstones (Fig. 48). The shales range from massive and thickly bedded to laminated. The basal Hot Shale member consists of organic rich black shales containing high TOC values (up to 16.7%). It is characterized by anomalous high levels of radioactivity closely related to the presence of uranium. The formation contains abundance of graptolites, but the higher sequences become progressively more brackish and graptolites are replaced by ostracods in the upper part of the section. According to Massa and Jaeger (1971), the Tanezzuft Formation yielded the following graptolite assemblage:

Climacograptus innotatus (Nicholson)
C. aff. *scalaris miserabilis* Elles and Wood
C. cf. *phrygionius* Tornquist
C. hughesi (Nicholson)
Monograptus cf. *atavus* Jones
M. revolutus Kurck
M. gregarious Lapworth
M. aff. *tenuis* Portlock

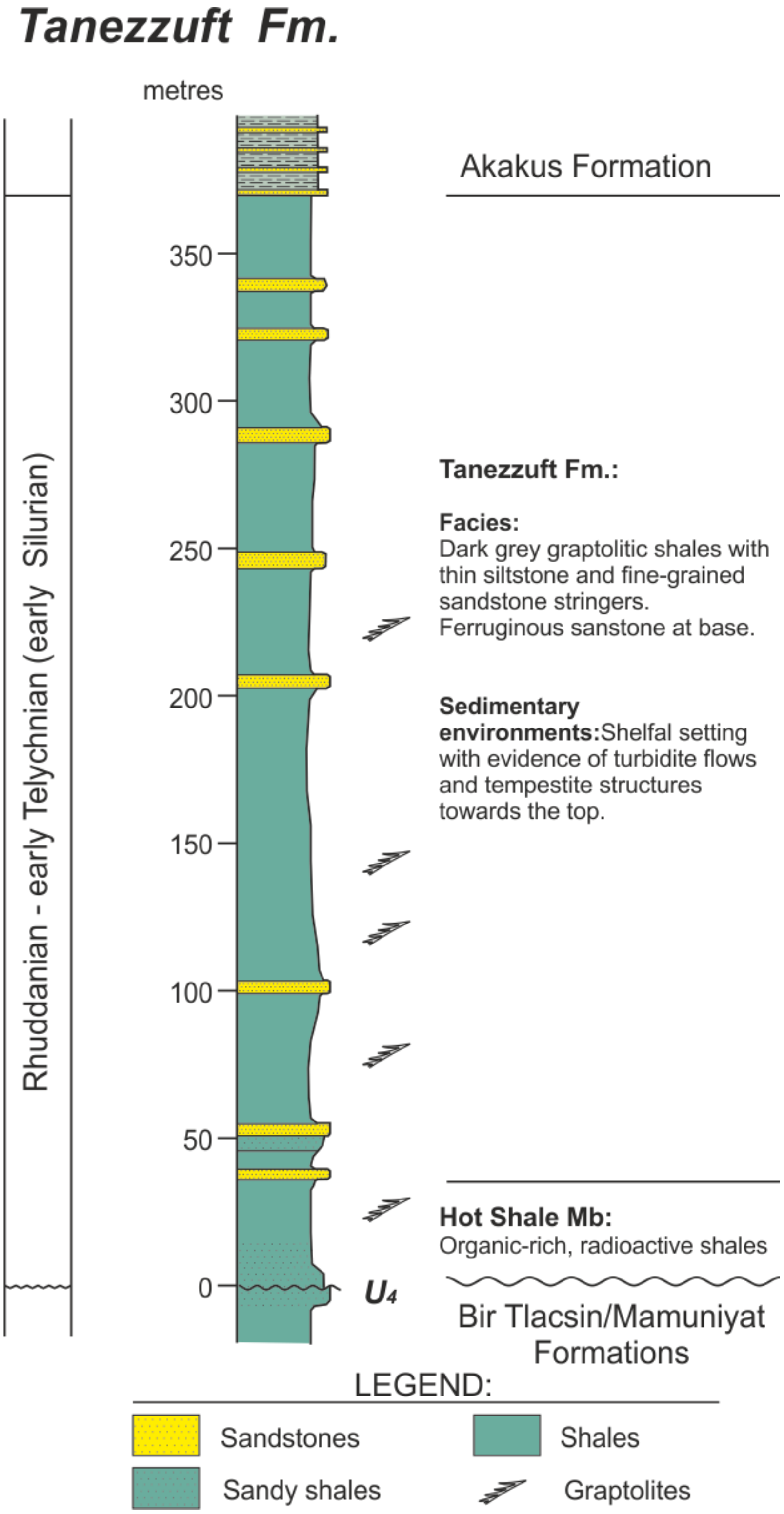


Figure 44.- Stratigraphic type section for the Tanezzuft Formation. Redraw from Radulovic (1984). Surface U_4 represents the basin-scale unconformity shown in Fig.19.

Figure 45.- Image of the conglomeratic lag from the basal ravinement surface of the Tanezzuft Formation on the Mamuniyat Formation. See location in Fig. 46.

This fossil assemblage defined the British Graptolite biozone 19 and probably the basal part of the biozone 20, corresponding with the middle part of the Llandovery. However, Bellini and Massa (1980) demonstrate that Tanezzuft Formation is diachronous. They produced evidence to show that in the Murzuq Basin the Tanezzuft Formation is early and middle Llandoverian, in the southern Ghadamis Basin it is middle Llandoverian to Wenlockian in age, and in the northern Ghadamis Basin it is largely Wenlockian and Ludlovian in age. Based in the graptolites fossil record yielded by outcrops of the Tanezzuft Formation in the Gargaf high, Parizek et al. (1984) and Gundobin (1985) established a middle Landovery age for the unit. On the basis of a palynological study carried out on a number of wells of NC-115 concession, Miles (2001) proposes an age for the Tanezzuft Formation covering a time spam from Rhuddanian to the lower part of Telychnian, supporting the lower to middle Llandovery age of the formation in the Murzuq Basin. According to this author, deposition of Tanezzuft Formation represent a maximum of 8.5 Ma.

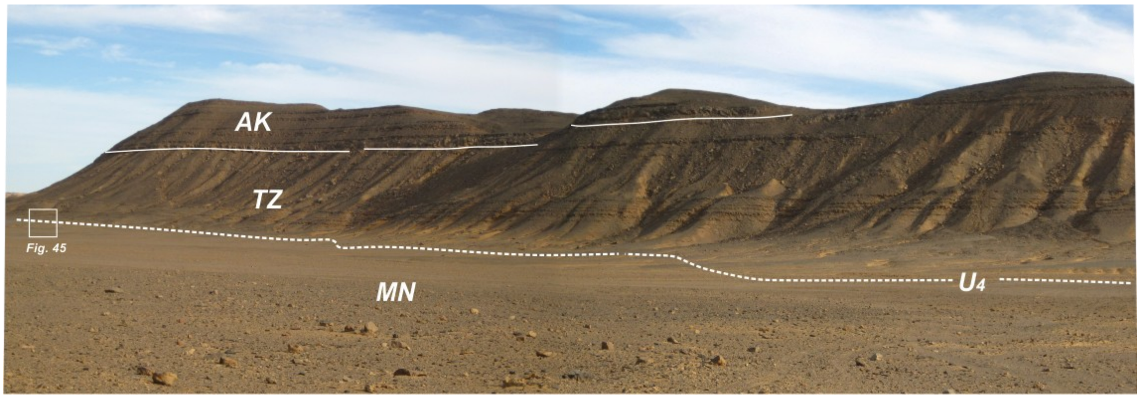


Figure 46.- Panoramic view of the Tanezzuft and basal Akakus section in the Jabal az-Zalmah, 200 km north of Kufrah. MN = Mamuniyat Fm. TZ = tanezzuft Fm. AK = Akakus Fm. Surface U_5 represents the basin-scale unconformity shown in Fig.19.

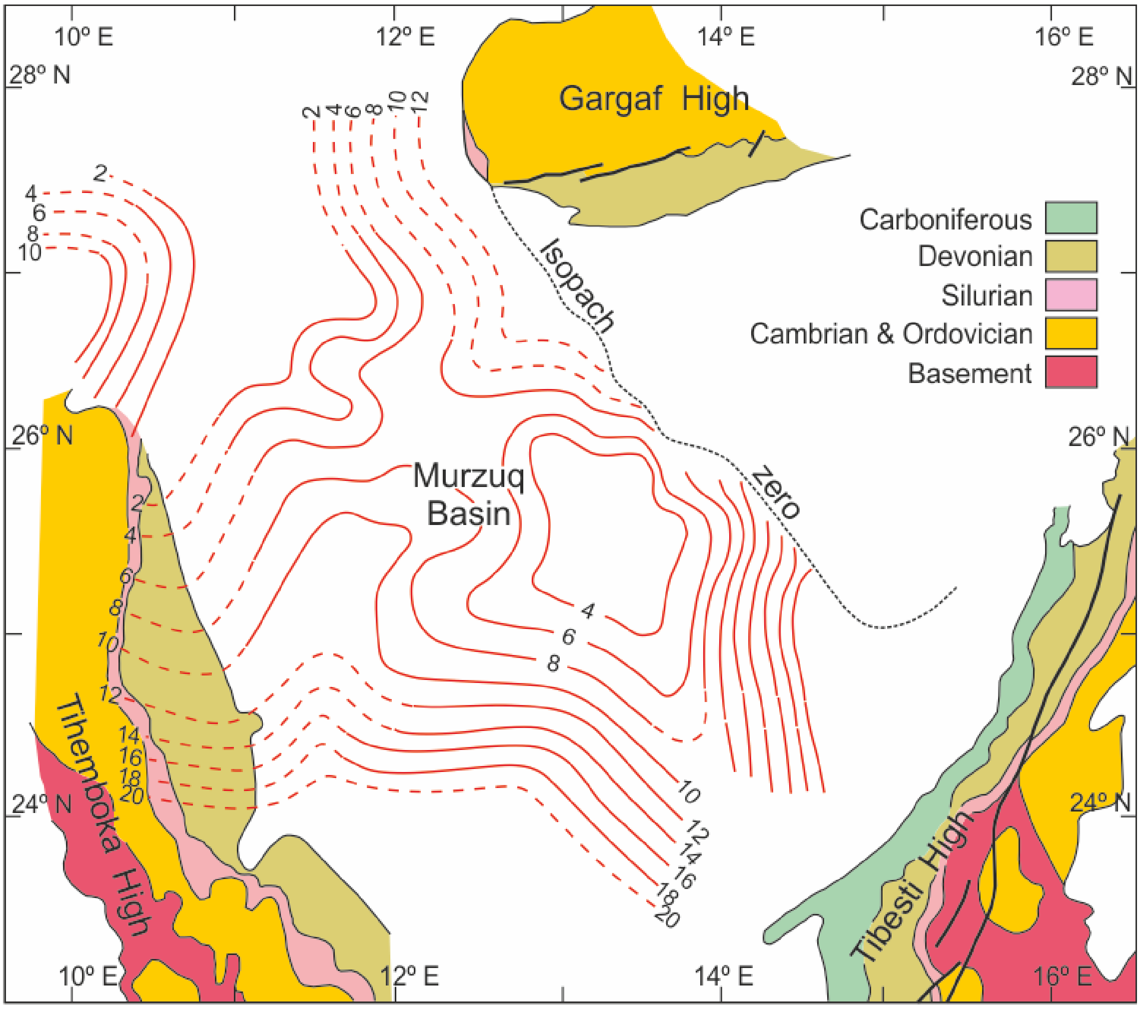
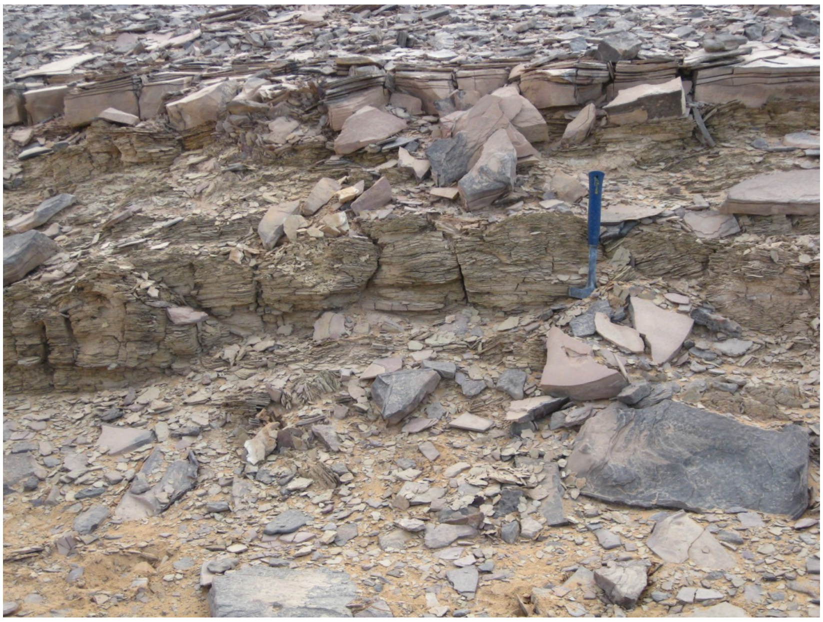


Figure 47.- Isolith map for the Murzuq Basin showing the sand percentage distribution of the Tanezzuft Formation. Contour interval = 2%. Redraw from Echikh and Sola (2000).

Figure 48.- Image of the laminated grey shales of the lower Tanezzuft Formation.



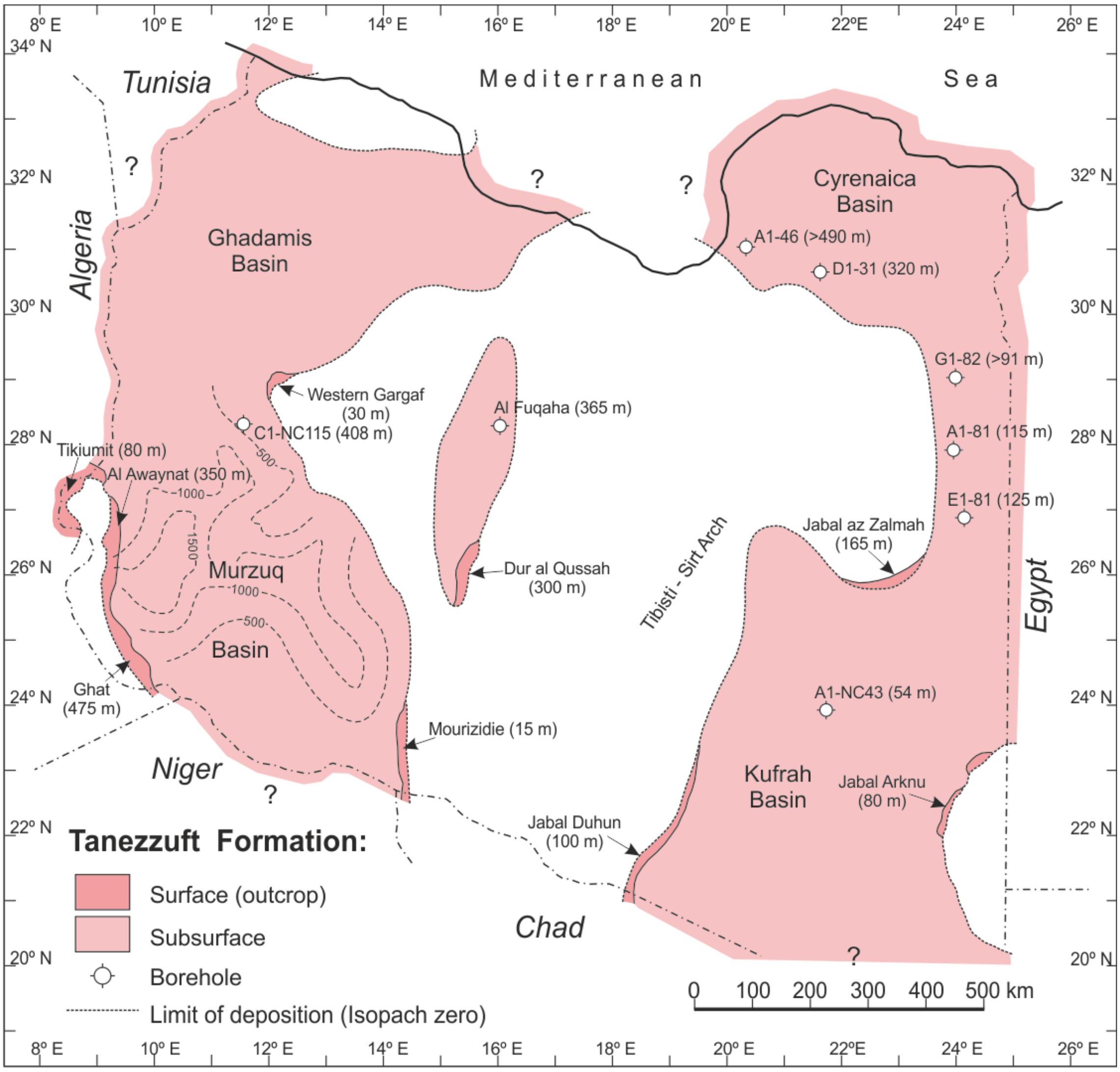


Figure 49.- Outcrop and subsurface extents of the Tanezzuft Formation in Libya. Isopach in Murzuq Basin in meters. Modified from Echikh and Sola (2000) and Hallett (2002).

In a sedimentological study based on both outcrop and core studies, de Castro et al. (1991) interpreted the lower Tanezzuft Formation as representing a predominantly turbiditic environment whilst the upper part is characterised by thick siltstone members showing hummocky cross stratification separated by hard ground, which he believed represent tempestite deposits. In any case, these sediments were deposited in restricted to open marine conditions associated with an early Silurian marine transgression. This was a consequence of the melting of the late Ordovician ice cap which originates a eustatic sea level rise (Echikh and Sola, 2000). The marine transgression took place over the Taconic erosional surface, and the Silurian transgression first flooded the topographic lows, and basal Hot Shale member were deposited within these closed basins. As sea-level rose the transgression spread over the remaining topographic highs, depositing normal outer-shelf shales. There is evidence that the Hot Shale member is present only about half the wells in the Murzuq Basin. Lüning et al (2000) published an isopach map of the hot shales in the area of concessions NC115 and NC174, on the northern edge of the Murzuq Basin, which showed the Hot Shales to be patchily developed in palaeotopographic lows on the pre-Silurian surface. The high uranium concentration which characterizes the highly radioactive Hot Shales, probably was originated by wind transpoted fine volcanic ash.

In a general sense, the organic-rich Hot Shales of the base of the Silurian sequence, plays a major role in the petroleum geology of Libya since it has been proven that these rocks are one of the major source rocks of north Africa and neighbouring regions (Davidson et al, 2000; Lüning et al, 2000, 2005).

The Tanezzuft Formation crops out in most of the margins and the subsurface of the Murzuq Basin (Fig. 49). The formation wedges out south of Dur al Qussah which suggests that it is absent fom the Brak-Bin-Ghanimal Uplift due to midde Devonian uplift and erosion. South of the uplift, in the Mourizide area, marine shales with graptolites reappear, although forming thin sequences.

On the western margin of the Murzuq Basin it has been mapped from Tikiumit to south Ghat on the border with Algeria and Niger varying in thickness from 475 m near Ghat to 350m near Al Awaynat to only 80 m at Tikiumit. In the western Gargaf, the Tanezzuft Formation has been mapped by Parizek et al. (1984) and Gundobin (1985) in the Qararat al Marar area, but only about 30 m is preserved due to middle Devonian erosion. In the Mourizidie area a thin Tanezzuft sequence, only 15 m thick, directly overlies the basement rocks (Bellini and Massa, 1980). The Tanezzuft Formation has been also recognized in the Dur al Qussah Trough where 200 to 300 m of silty sandstones and shales are present. The Tanezzuft Formation crops out around the al Kufrah Basin showing an unconformable contact with the underlying Cambro-Ordovician sandstones. In this area their thickness ranges from about 80 m in the southeast to over 100 m in the southwest and reaches up to 165 m in the northeastern sector. The Tanezzuft Formation is present in the A1-NC43 and B1-NC43 wells drilled by Agip in 1978 and 1980 (Fig. 49).

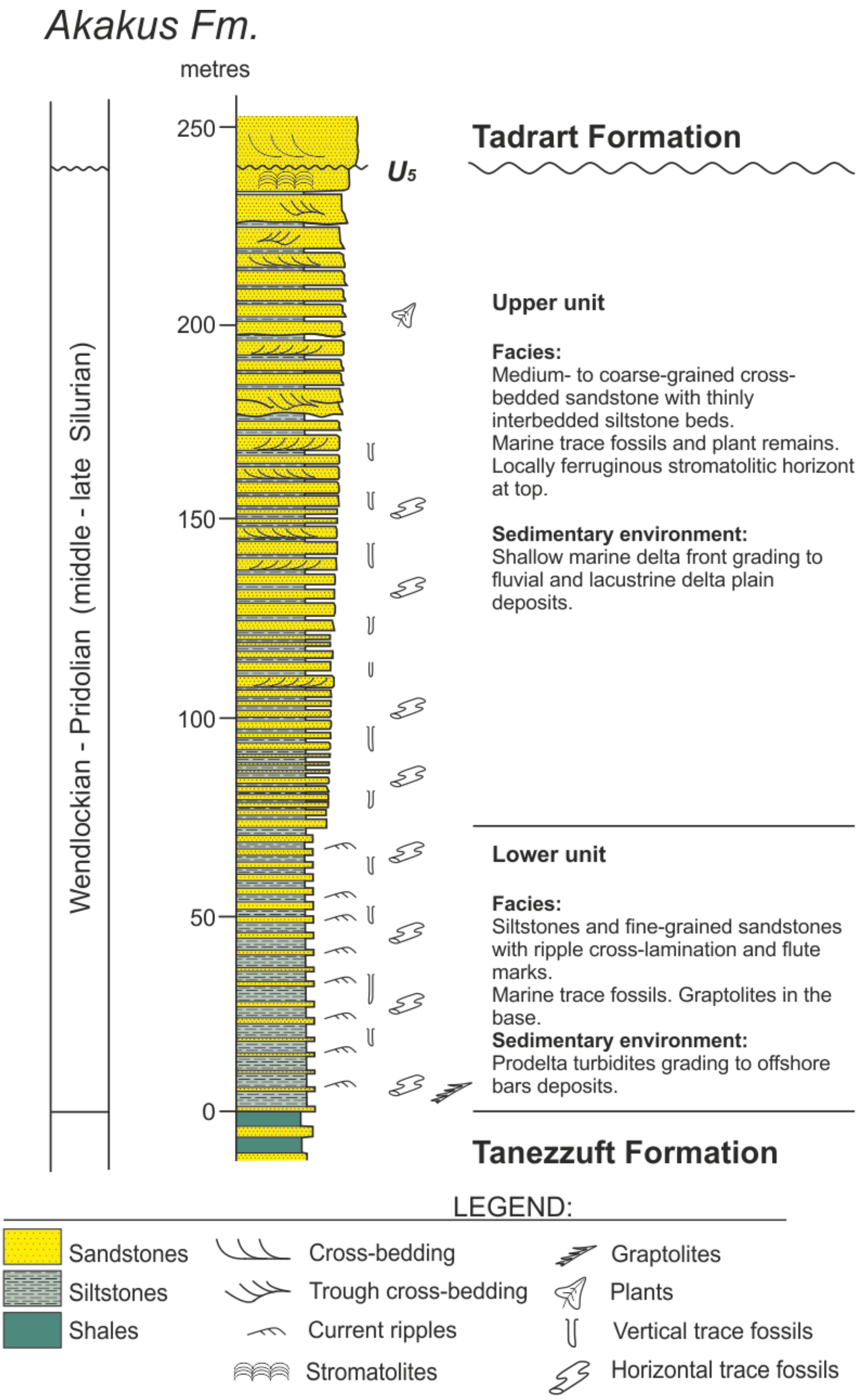
In the subsurface of the Murzuq Basin the thickness distribution of the Tanezzuft Formation draws a depocenter were most than 1500 m of shales were accumulated. The formation has been drilled by most of the wells, ranging in thickness from 45 m to 320 m It is present in wells H1-NC 58 and F1-NC 58 where it shows evidence of turbidite flows but it is missing in the NC 101 wells, on the Brak-Bin Ghanimah Uplift, at Sabha and in the A1-73, A1-64, A1-77 and B1-77 wells, due to middle Devonian erosion. The Hot Shale member is present in only about half the wells in the Murzuq Basin.

3.2.8. Akakus Formation

Formerly, the Akakus sequence was first described by Killian (1928) as the lower part of his "*Gres Superieurs du Tassili*" in the western flanks of the Murzuq Basin: This was later named by Desio (1936b) as Akakus Sandstone in the Jabal Akakus, 50 km north of Ghat, but no type section was designated by Desio (1936b). Klitzsch (1969) proposed a type section for the Akakus Formation at Takarkhouri pass, 50 km south of Ghat, but further studies carried out by Klitzsch et al. (1973) in the eastern Murzuq Basin demonstrated that the type section proposed by Klitzsch (1969) represents only the lower part of the Akakus Formation, and a neostratotype 240 m thick was proposed (Fig. 50). The base of the formation is gradational to the Tanezzuft Formation, whereas the top is made by a sharp and erosive contact to the overlying Tadrart sandstones. The Akakus Formation have been subdivided into three informal (lower, middle and upper) units by Echikh (1984) or in two (lower and upper) by Mamgain (1980). A number of authors highlight the diachronic nature of the Akakus Formation from south to north (Hallett, 2002).

Lithologically, the Akakus Formation constitutes a coarsening upwards sequence made up by thin to thickly bedded sandstone with interbedded siltstone and shales (Fig. 50). In the base, the shale and silty sandstone layers forming the top of the Tanezzuft Formation pass gradually into the overlaying sands of the Akakus Formation (Fig. 46). In this way, the lower part of the formation is mainly constituted by fine-grained, white, brown to intensely red brown, occasionally ferruginous with ripple cross lamination and siltstone and shale intercalations (Fig. 51). The upper unit (Fig. 52) is dominantly constituted by thinly to thickly stratified medium- to coarse-grained sandstones mostly white, yellowish brown to intensely red brown in colour, occasionally ferruginous, cross-bedded, and convoluted in places. Locally the sandstones are poorly consolidated, porous, and quarzitic near the top. In the Dor el Gussa region, in the eastern part of Murzuq Basin, the upper part of the Akakus Formation mainly consists of green and red clays with interstratified ferruginous sandstone beds towards the top. In a number of places the top of the Akakus Formation is represented by a ferruginous sandstone bed containing algal stromatolites, which has been interpreted as a stratigraphic break between the Akakus and the overlying Tadrart Formation.

The shales of the lower part contain graptolites. Klitzsch (1969) has recorded the a graptolite assemblage constituted by *Climacograptus hughesi* (Nicolson); *Monograptus atavus* Jones; *M.* cf. *concinnus* Lapworth and *M. lobiferus* McCoy, indicating a middle Llandoverian age (zone 19 to the basal part of zone 20 of the British scale). The sandstones are intensively bioturbated, and contain abundance of *Skolithos*, *Arthrohycus*, *Cruziana* (*C. acacensis*; *C. irregularis,* Fig. 53) and Rusophycus (*R. bilobatus*) trace fossils (Plauchut and Faure, 1960; Massa and Jaeger, 1971). Seilacher (2000) defined *Arthrophycus*



Upper unit

Facies:
Medium- to coarse-grained cross-bedded sandstone with thinly interbedded siltstone beds.
Marine trace fossils and plant remains.
Locally ferruginous stromatolitic horizont at top.

Sedimentary environment:
Shallow marine delta front grading to fluvial and lacustrine delta plain deposits.

Lower unit

Facies:
Siltstones and fine-grained sandstones with ripple cross-lamination and flute marks.
Marine trace fossils. Graptolites in the base.
Sedimentary environment:
Prodelta turbidites grading to offshore bars deposits.

Figure 50.- Proposed type section for the Akakus Formation. Surface U_5 represents the Caledonian basin-scale unconformity shown in Fig.19.

lateralis, a new ichnospecie from the type section. The red and green clays of the upper part of the Formation in the eastern Murzuq Basin has yielded forms of *Psilophytes* and *Lycophytes* remains, two groups of primitive vascular plants. A general Wenlockian to Pridolian (middle Silurian) age has been assigned to the Akakus Formation.

The Akakus Formation constituted a coarsening upwards sequence recording a delta progradation, from the basal prodelta turbidites, offshore bars, shallow marine to littoral and finally non-marine fluvial and lacustrine deposits at top. Locally the formation is capped by a ferruginous stromatolitic horizon which suggests subaerial exposure in relation to the Caledonian unconformity.

The Akakus Formation is present in most of Libya (Fig. 54). It has been recorded in the subsurface of Cyrenaica and Kufrah basins and crops out in the SW, SE and NE borders of the Kufrah Basin, where it shows thicknesses ranging from 2 to 160 m. In the SW part of the Kufrah Basin the upper part of the Formation is missing, and the outcropping sequences represent the residual thickness. The Akakus Formation is well developed in the subsurface of the Hammadah basin, and crops out in the Dur el Qussah region, where Klitzsch (1963) recorded a 465 m thick section. The formation is also present in the subsurface of the Ghadamis Basin.

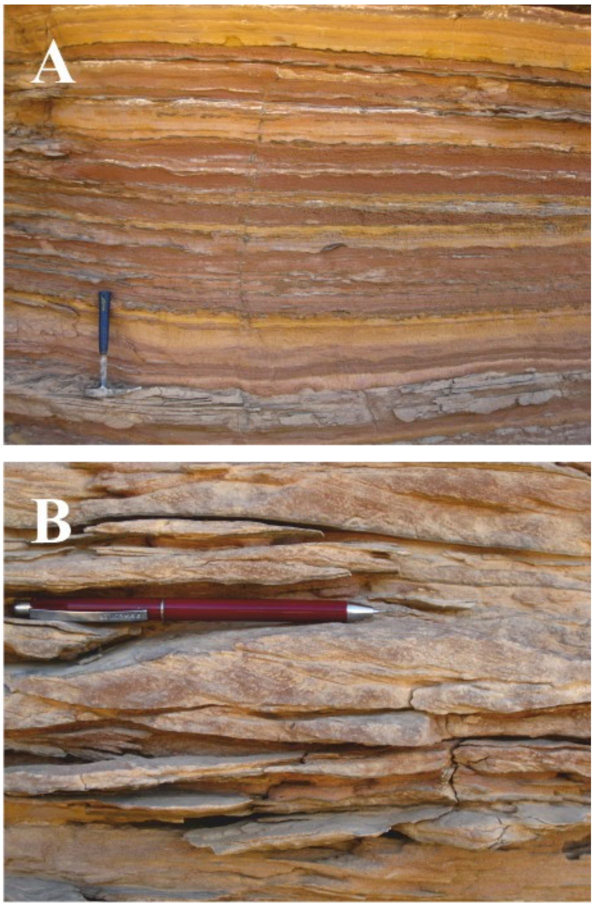


Figure 51.- A) Field view of the thinly stratified siltstone and fine-grained sandstone of the lower unit of the Akakus Formation. **B)** Detail of the ripple cross-laminated fine-grained sandstone of the lower unit of the Akakus Formation.

Figure 52.- Field view of the thickly stratified sandstones of the upper unit of the Akakus Formation. The arrow shows the limit with the lower unit.

In the Murzuq Basin the formation is present in the subsurface of the eastern and northeastern parts and crops out in the western and southeastern bordes of the basin (Fig. 54). Over the Gargaf structural high the formation has been completely eroded. Wells of licences NC115 and NC186 have not recorded the Aakus sandstones or only thin remmants have been encountered in the southwestern wells D1- and E1-NC115. However, wells A1-76, H1-NC58 and F1-NC58, located southwest, drilled important thicknesses of the formation, the last one up to 560 meters. In licence NC115 the Tanezzuft Formation is truncated by an erosive surface and Basal Devonian Sandstone beds unconformably rest on the Tanezzuft shales. According to Aziz (2000), the late Silurian Caledonian uplift have removed the Akakus sandstones from most of the license area.

Figure 53.- Cruziana trace fossil from the upper unit of the Akakus Formation.

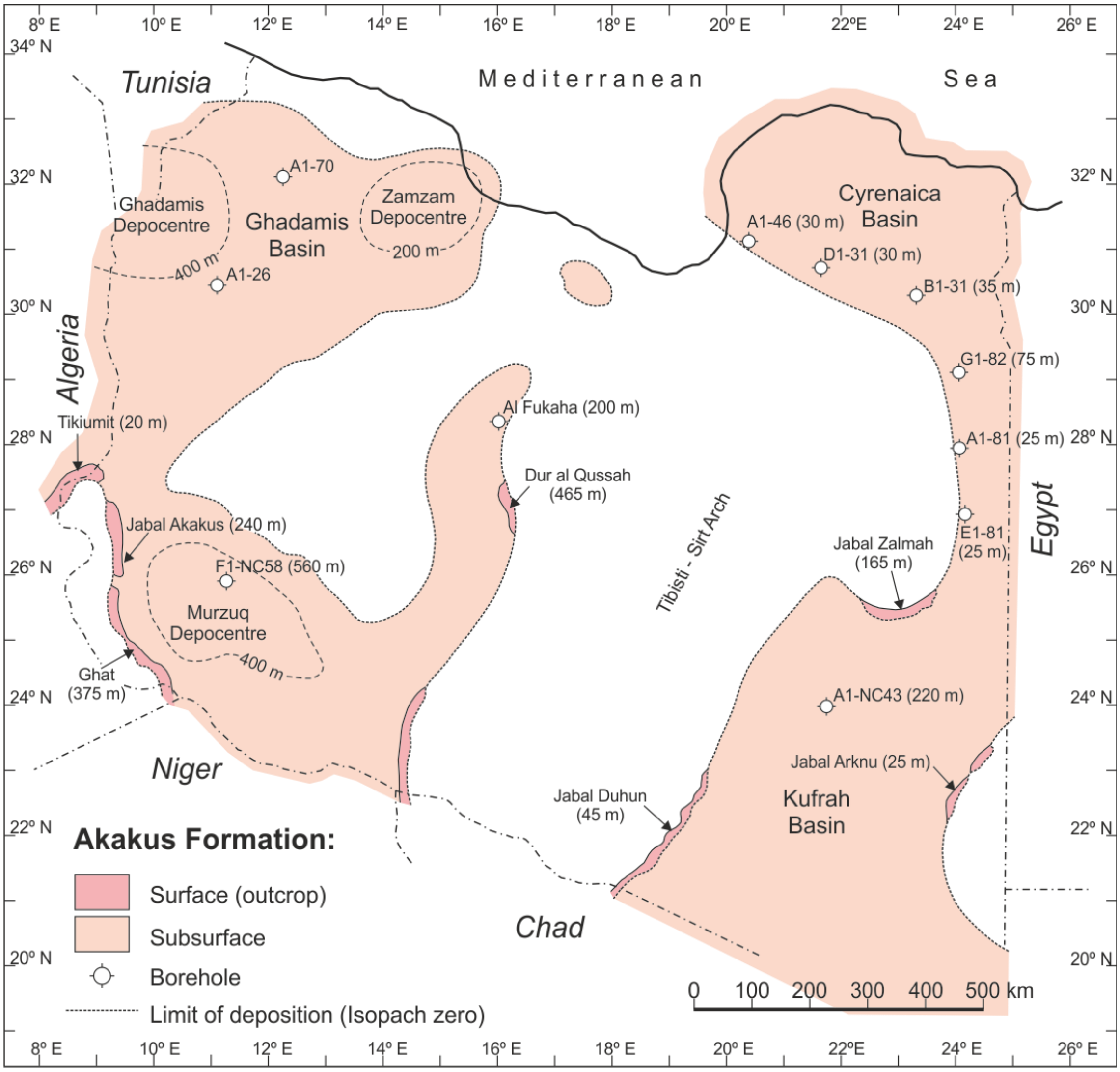


Figure 54.- Outcrop and subsurface extents of the Akakus Formation in Libya. Modified from Hallett (2002).

3.2.9. Tadrart Formation

The term “Gres du Tadrart” was probably first introduced by Collomb in a manuscript dated in 1958, and later adopted by Burollet (1960) and Massa and Collomb (1960) as Tadrart Sandstone (Mamgain, 1980). A 140 m thick type section was suppliyed by Klizsch (1969) from the Jabal Tadrart, in the western margin of the Murzuq Basin 35 km south of Ghat (Fig. 55). The Tadrart Formation overlies an unconformity surface (U_6 in Figs. 19 and 56) developed on the late Silurian succesion which is considered as the result of the Caledonian orogeny (Hallett, 2002; El Hawat and Ben Rahuma, 2008). In most of Libya the Caledonian unconformity constitutes a major erosional hiatus separating the two formations, but in the centre of the Ghadamis and Cyrenaica basins deposition of the Tadrart Formation may have been continuous with the underlying Akakus Formation. The top is conformable with the overlying Wan Kasa Formation. Lithologycally, the Tadrart Formation is monotonous, and it displays no evident lateral facies changes.

In the type locality, the Tadrart Formation could be divided into two units (Fig. 55). The lower unit is dominantly made up by lenticular bodies of ferruginous, massive to trough cross-bedded, fine- to coarse-grained conglomeratic even sandstones (Fig. 57) forming fining-upwards sequences. Fossil record is scarce, and consists of micro- and macroflora remains. The upper unit consists of massive to locally herring-bone cross-bedded, medium-grained sandstone with minor siltstone. Marine trace fossils as *Cruziana* and *Skolithos* are frequent. In the Dur al Qussah area (eastern Murzuq Basin), plant fragments resembling *Lepidodendron* have been reported from the lower unit, as well as poorly preserved fossil fish from the interbedded siltstones of the upper unit. There are not available data about the petrophysical properties of the Tadrart sandstones in the Murzuq Basin, but in the Ghadamis Basin, where the formation is widely distributed, it has good porosity values, particularly on the southern flank of the basin, where the formation becomes an excellent petroleum reservoir in the area.

Sedimentological analysis of the Tadrart Formation in the western flank of the Murzuq basin has been carried out by Clark-Lowes (1978), Massa (1988) and Adamson et al (2000). According to these authors, the lower Tadrart unit records deposition in a fluvial braided environment, whilst the upper Tadrart unit records deposition in a shallow marine environment, with shoreline facies cut by tidal channels, and tidal influence increasing upwards. So, the Tadrart Formation constitutes a deepening sequence recording a marine transgression affecting a wide area on the uplifted, and eroded pre-Devonian surface.

No age diagnostic fossils have been found in the Murzuq Basin wells, but based on its ichnofacies and its relation to under- and overlying units, the age

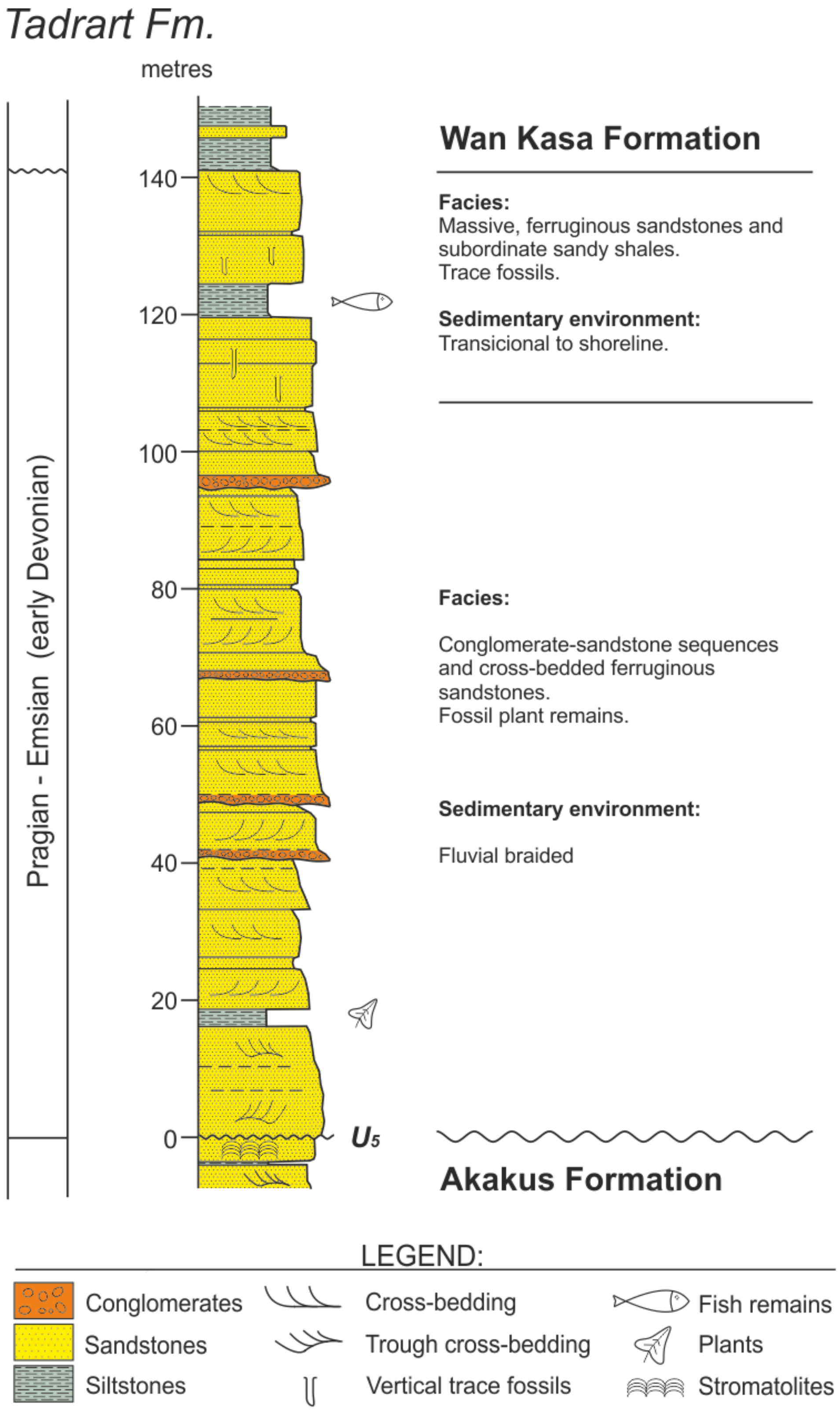


Figure 55.- Stratigraphic type section for the Tadrart Formation. Modified from Radulovic (1984). Surface U_5 represents the Caledonian basin-scale unconformity shown in Fig.19.

Figure 56.- Field view of the unconformity (U_5) between the Akakus (**AK**) and Tadrart (**TD**) formations. The image was taken in the Jabal al-Zalmah, 230 km north of Kufrah, in the Kufrah Basin.

of the Tadrart Formation is assumed to be early Devonian (Mergl and Massa, 2000). On the basis of a palynological study in the Al Awaynat area, Belhaj (2000) suggests an age from Gedinnian to late Emsian (early Devonian). In Jabal Zalmah, in the Kufrah Basin, Pragian microfloras have been reported from the Tadrart Formation, and a similar sequence drilled by wells A1 and B1-NC43 yielded a rich microflora which indicates a Pragian age. In both cases, Lochkovian sequence is missing in the Kufrah Basin In the Ghadamis Basin, where the Tadrart Formation

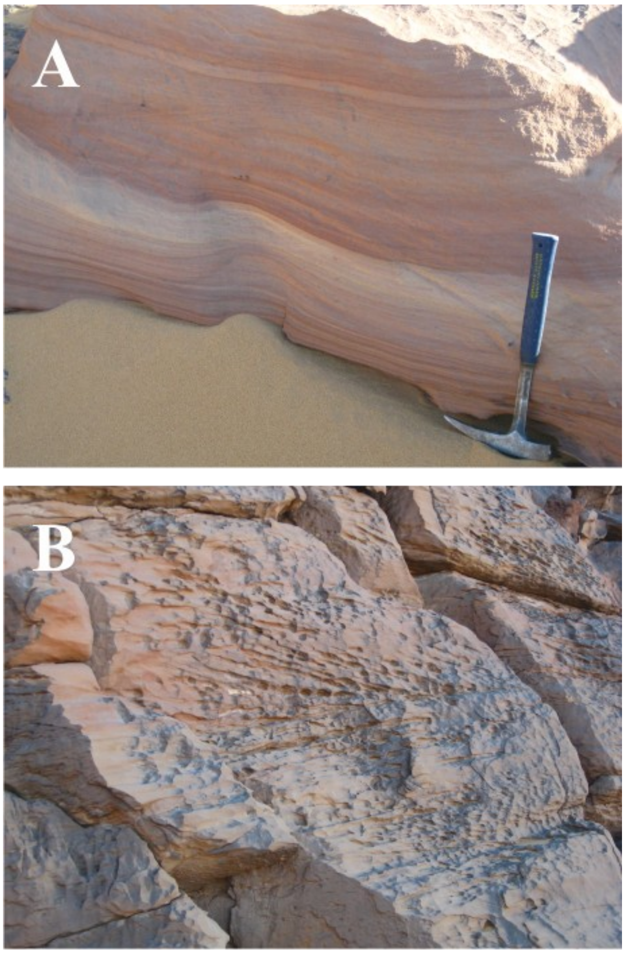


Figure 57.- Detail of the red coloured cross-laminated sandstones of the lower unit of the Tadrart Formation.

has been penetrated by many wells, the presence of abundant plant remains and miospores has allowed dating the Tadrart Formation as Pragian to early Emsian, but palynological analysis of well D1-8 in the centre of the Ghadamis Basin demonstrated that Tadrart deposition began during the Lochkovian in the Ghadamis centre (Hallett, 2002).

The Tadrart Formation widely extents across the Ghadamis and Kufrah basins, but it fills only partially the Murzuq Basin and it is absent in the Cyrenaica and Sirt basins (Fig. 58). The present-day distribution of the Tadrart Formation within the Murzuq Basin has been greatly affected by the middle Devonian Caledonian orogeny, and the thick Tadrart sequence cropping out in the Dur al Qussah and Al Awaynat areas, is missing over much of the central part of the Murzuq Basin (Fig. 58). The Tadrart Formation crops out forming a

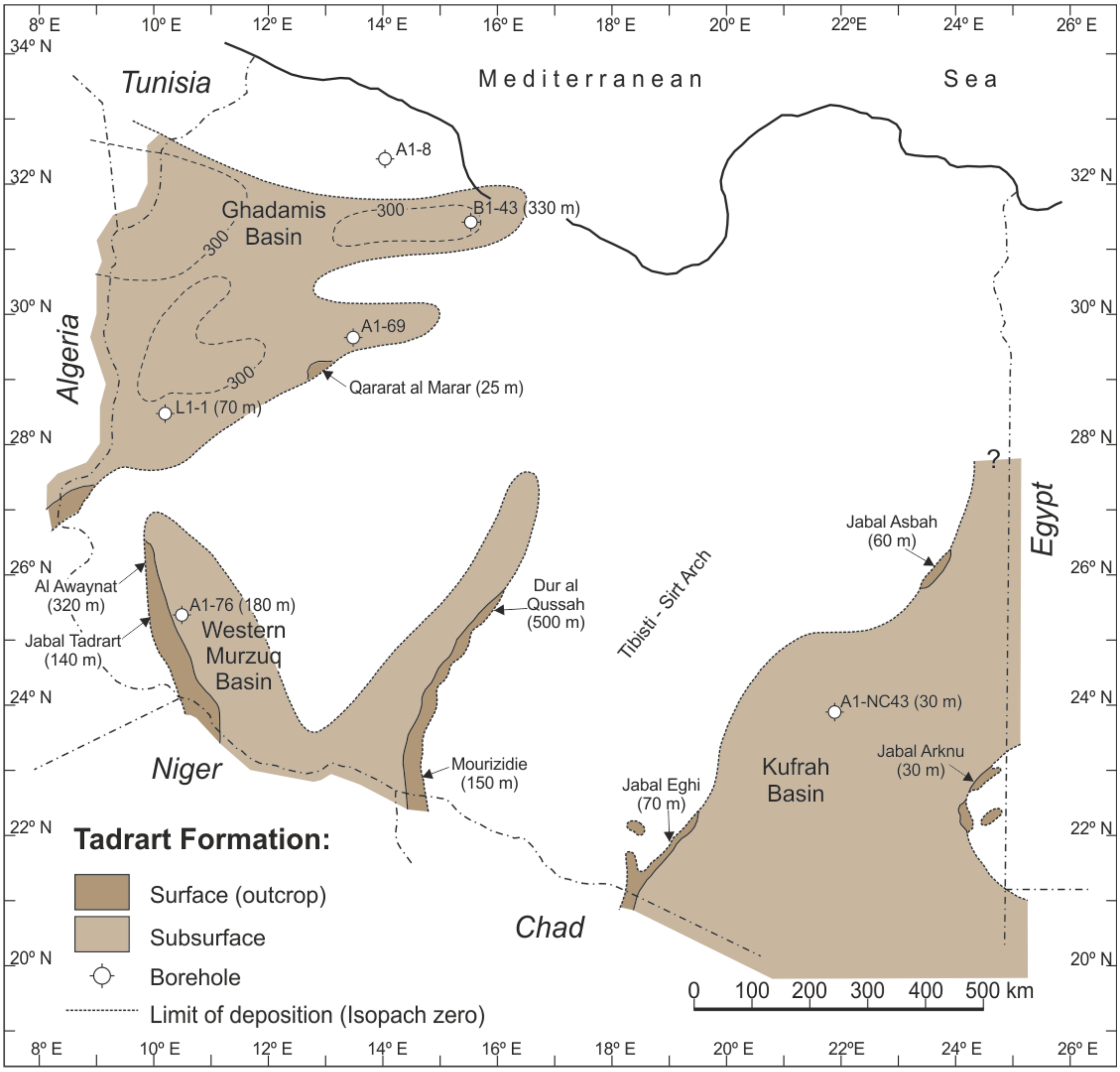


Figure 58.- Outcrop and subsurface extents of the Tadrart Formation in Libya. Modified from Hallett (2002).

fringe along the western flank of the Murzuq Basin from Tikiumit to the border with Niger. Their thickness in this area reaches up to 320 m. In the subsurface of the Murzuq Basin the Tadrart Formation has been drilled by wells A1-76 and H1-NC58, located in the western Murzuq. It has been not penetrated in wells from NC115 and NC186.

3.2.10. Wan Kasa Formation

The Wan Kasa Formation was first described by Borghi and Chiesa (1940) from the wadi Wan Kasa in the western boundary of the Murzuq Basin. A 55 m thick type section was formally established by Klitzsch (1965, 1969) in the same area. In the type area the base of the Wan Kasa Formation is a conformable boundary on the Tadrat Formation, whereas the top is constituted by a middle Devonian erosive surface (U_7 in Fig. 19) which is unconformably overlain by the Awaynat Wanin Formation. The Wan Kasa Formation crops out largely in the western flank of the Murzuq Basin, from Tikiumit to south Anay. It shows similar characteristics to the type area along this belt, and their thickness ranges from less than 10 m at Tikiumit to more than 50 m at Anay. In the type area the Wan Kasa Formation consists of an alternation of thinly bedded silt, silty clay and fine-grained sandstone beds with thin layers of gypsum and oolitic ferruginous levels. The siltstones are light gray to redish coloured, ferruginous and occasionally calcareous. According to El Hawat and Ben Rahuma (2008), the percentage of primary carbonate beds varies from 15% to 25%. Siltstones and fine-grained sandstones show wavy and flasser lamination, grading upwards to more massive cross-bedded sandstones at the top.

In the type area the Wan Kasa Formation contains conodonts, tentaculitids, brachiopods, bivalves, trilobite and marine trace fossils. Klitzsch (1963) reported the presence of *Lingula* sp. *Discina* sp. and plates of Placoderm fishes (*Aerthrodirea* and *Antiarchchia*) from the eastern flank of Murzuq Basin. Based on the rich fauna of brachiopods Borghi and Chiesa (1940) and Klitzsch (1965, 1969) proposed an Eifelian (middle Devonian) age for the Wan Kasa Formation, but Mergl and Massa (2000) in a synthesis of several palaeontological studies of the Devonian and Carboniferous faunas of the Murzuq Basin considers that this fossil assemblage has a pre-Eifelian character. These authors found that the commonest species recorded in the Wan Kasa Formation from the type area is the acrospiriferid brachiopod *Spinella paulula*; the genus *Spinella* is well known in the Emsian of Australia and Nevada, and the trilobite *Homalanotus (Dipleura) simplex* also indicates a general Emsian age. On the other hand, Hajlasz et al (1978) found within the siltstones and fine-grained sandstones abundant tentaculitid remains, recognizing the presence of *Vlajovites* cf. *antarcticus*, *Styliolina uralica* and *S. glabra*, which are know elsewhere from the early Devonian, together with a microfauna of the arenaceous primitive forms *Parathurammina* and *Irregularina*, reported from the early Devonian of Siberia. Evidence from other areas in the Murzuq borders also supported an Emsian age (Borghi and Chiesa, 1940; Klitzsch, 1965, 1969; Grubic et al., 1991; Mergl and Massa, 1992). Consequently, we attributed an Emsian (early Devonian) age to the Wan Kasa Formation in the western Murzuq type area. In the subsurface of the Kufrah Basin the Wan Kasa Formation has been drilled by wells A1- and B1-NC43. The section yielded abundance of palinological remains which confirm the Emsian age of this sequence (Grignani et al, 1991).

The Wan Kasa Formation records deposition in a low-energy marine setting, ranging from shallow sublitoral to offshore environments. Sedimentological studies carried out by Clark-Lowes (1978) demonstrated that Wan Kasa sequence accumulated in an environment dominated by strong tides, with evidence of deposition from sediment-laden sub-tidal currents. Sutcliffe et al (2000) recognized facies associations indicative of oolitic shelf and muddy shoreface to tidal-flat environments.

Besides the western border, the Wan Kasa Formation crops out in the eastern flank of the Murzuq Basin forming a 120 km long belt from the Dur al Qussah to the Mourizidae. In the Dur al Qussah Trough the formation reach their maximum thickness (120 m) and pinch out northwards and southwards. In the Murzuq subsurface the Wan Kasa Formation has been reported from wells A1-76 and H1-NC58 wells, but it is absent to the northeast of these wells (Echikh and Sola, 2000). The formation is not present in the centre of the basin does to the middle Devonian tectonism and erosion. It is also absent in well A1 -67, A1-73 and all the wells drilled in NC115 and NC186 concessions. The Wan Kasa Formation has not been recognized in the Gargaf high, but it reappears northwards, in the subsurface of the Ghadamis Basin where is has been drilled by a great number of boreholes, reaching up to 365 m in thickness in well E1-8 (Belhaj, 1996), and extents westwards into Algeria and the Illizi Basin, where the Wan Kasa sandstones constitutes a good oil reservoir (Aliev et al, 1971; Massa and Moreau-Benoit, 1976; Belhaj, 1996; Echikh, 1998).

In the Kufrah Basin the Wan Kasa Formation crops out in eastern and western borders, reaching thicknesses ranging from 20 to 60 m. In the subsurface the formation has been drilled by wells A1- and B1-NC43, and northwards it has been recorded in the eastern Cyrenaica Basin by J1-81 and A1-84 wells. The Wan Kasa Formation is not present in the Sirt Basin.

3.2.11. Awaynat Wanin Formation

The term Awainat Wanin was first introduced by Lelubre (1946) to describe the Devonian rock exposures on the western Gargaf. This stratigraphic nomenclature was later used by Massa and Collom (1960), but subsequent attempts to improve the definition introduce considerable confusion. A summary is shown in figure 59. After the Lelubre's description, Collomb (1962) subdivided the entire Awainat Wanin and the lower part of the overlying Marar formations into eight cycles, restricting the Awaynat Wanin Formation to the four lower cycles and proposing the name Chatti Formation for the upper four cycles. Latter, Massa and Moreau-Benoit (1976) upgrade the Awaynat Wanin to Group rank, splitting it into four new formations named as Awaynat Wanin I to IV. The Awainat Wanin I to IV new formations were not lithologically defined, but biostratigraphically corresponding to the stages Eiffelian, Givetian, Frasnian and Fammenian. The Marar Formation remains unaltered and the remainder strata were assigned to the previously defined (Termier and Termier, 1974) Tahara Formation (Fig. 59). In 1984 the Industrial Research Centre of Tripoli, intro-

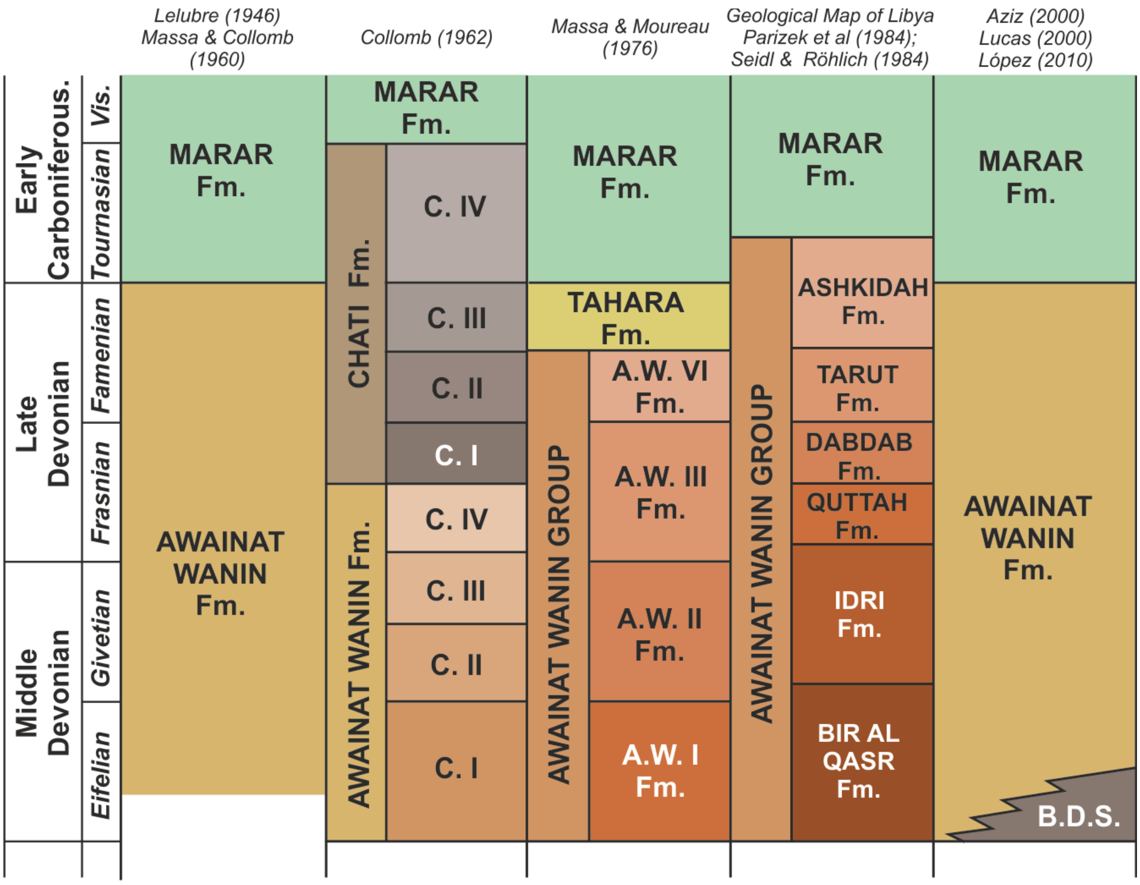


Figure 59.- Correspondence within the different lithostratigraphic proposals for the middle and late Devonian rocks. See text for explanation.

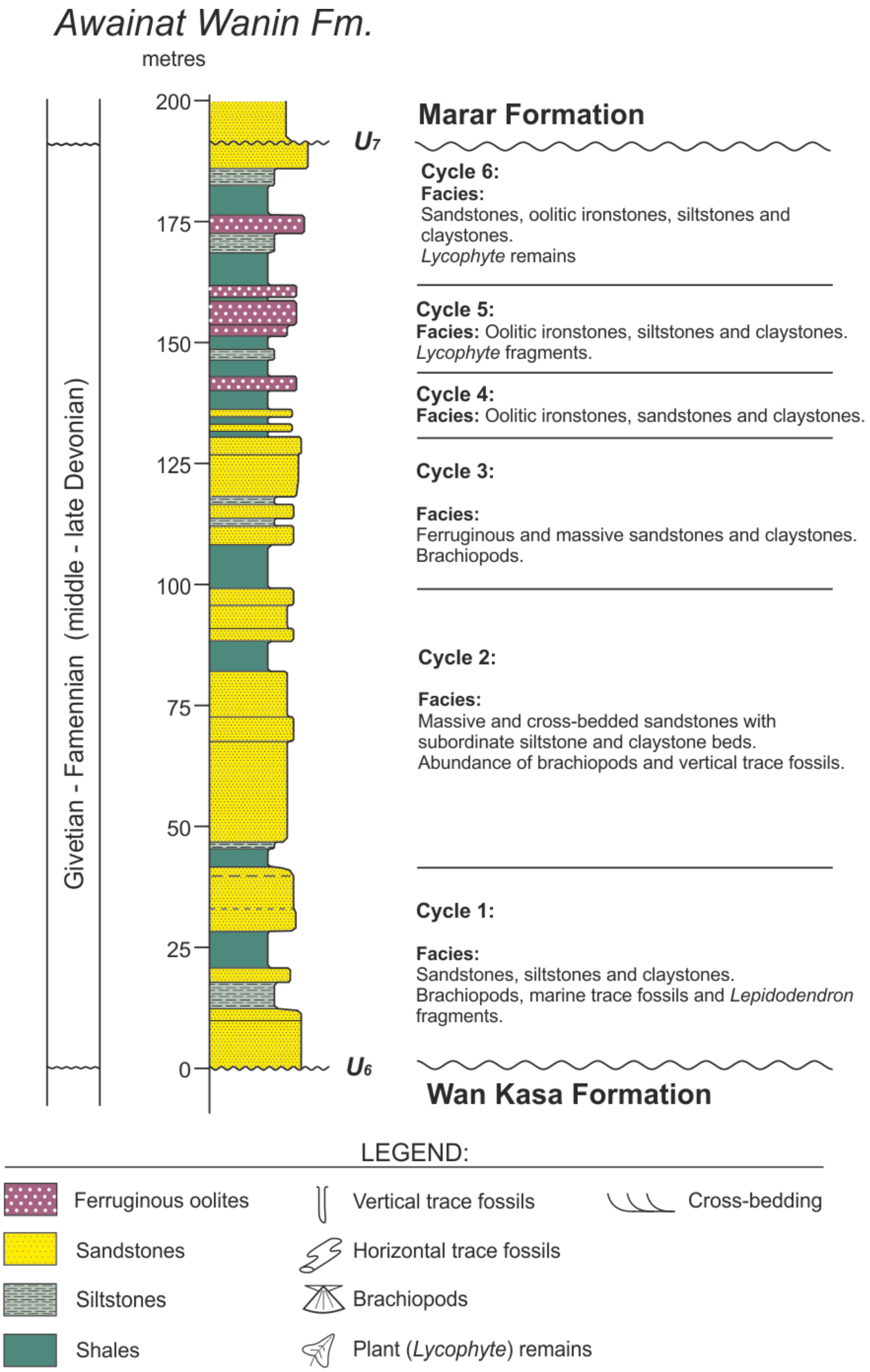


Figure 60.- Stratigraphic type section for the Awainat Wanin Formation. Modified from Parizek et al. (1984) and Seidl and Rohlich (1984). Surfaces U_6 and U_7 represents the basin-scale unconformities shown in Fig.19.

duce a new stratigraphic nomenclature for the Idri, Sabha and Al Fuqaha map-sheets of the Geological Map of Libya (Parizek et al., 1984; Seidl and Röhlich, 1984). These authors redefine the Awainat Wanin Group, including the Tahara Formation and the basal part of the Marar, and subdivide it into six new formations, from base to top: Bir Al Qasr, Idri, Quttah, Dabdab, Tarut and Ashkidah formations. Actually, most of the stratigraphic works become to the former Lelubre's proposal (Aziz, 2000; Echikh and Sola, 2000; Hallett, 2002; El Hawat and Ben Rahuma, 2008; López, 2010). Furthermore, in the subsurface, a production unit located in the base of the middle to late Devonian sequence is frequently used. It refers to the Basal Devonian Sandstone unit (Aziz, 2000; Lucas, 2000; López, 2010).

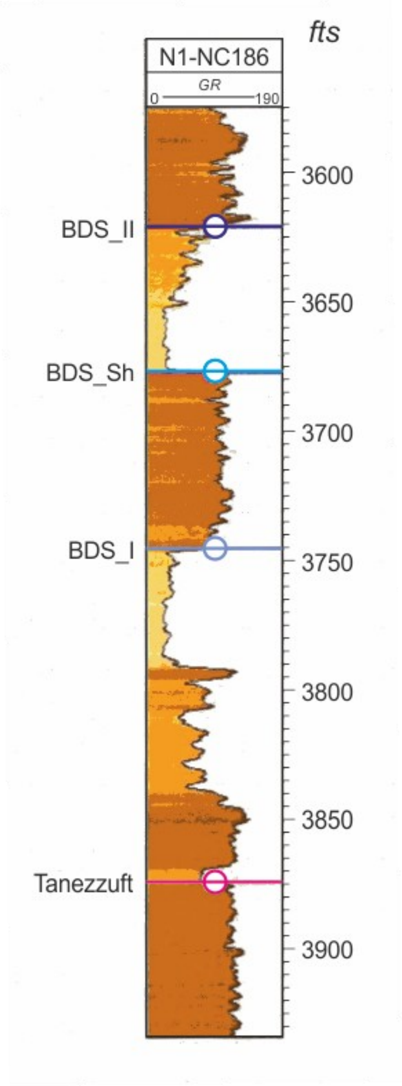


Figure 61.- Gamma Ray log for the BDS interval and BDS' subdivision in well N1-NC186.

The type section for the Awaynat Wanin Formation was formerly stablished in the northwestern Gargaf as the entire sequence between the top of the Wan Kasa Formation and the base of the Marar Formation. It reaches about 160 – 200 metres thick. The basal boundary with the Wan Kasa Formation is an unconformity (U_7 in Fig. 19). The top is also an unconformity (U_8 in Fig. 19) with the overlying Marar Formation. The basal unconformity is a erosive surface related to late Lower Devonian tectonism which produced local uplift, erosion and peneplaination, resulting in the removal of older rocks. A part of the Awainat Wanin Formation was accumulated onto the eroded surface, and in wide areas of the Murzuq basin the Awainat Wanin Formation directly rest on the Silurian or older sequences. Generally, in these areas the Basal Devonian Sandstone (BDS) interval which constitutes the base of the Awainat Wanin Formation represents the transgressive track on the erosional relief.

The Awainat Wanin Formation type section (Fig. 60) consists of rhythmic alternations of thick to thin beds of sandstone, siltstone and shale with occasional iron oolitic beds. The sandstones are very fine to medium-grained, frequently cross-bedded and contain a varied fauna of brachiopods. Locally brachiopods shells are found concentrated forming coquina beds. Claystones sometimes are ferruginous or gypsiferous. *Spirophyton* trace fossils have been reported. The Awainat Wanin succession is arranged forming six, 15 to 30 m thick stacked depositional sequences accumulated within a progradational deltaic sequence.

In the subsurface the base of the Awainat Wanin Formation is constituted by the BDS interval, a thin and irregular sandy unit clearly filling Caledonian erosional relief which is widely distributed in the north and northeastern Murzuq Basin. For operative purposes it has been divided into two sandstone members (BDS-I and BDS-II), separated by a shaly unit (BDSh) (Fig. 61). The two sandy members are best developped eastwards, and the entire BDS inter-

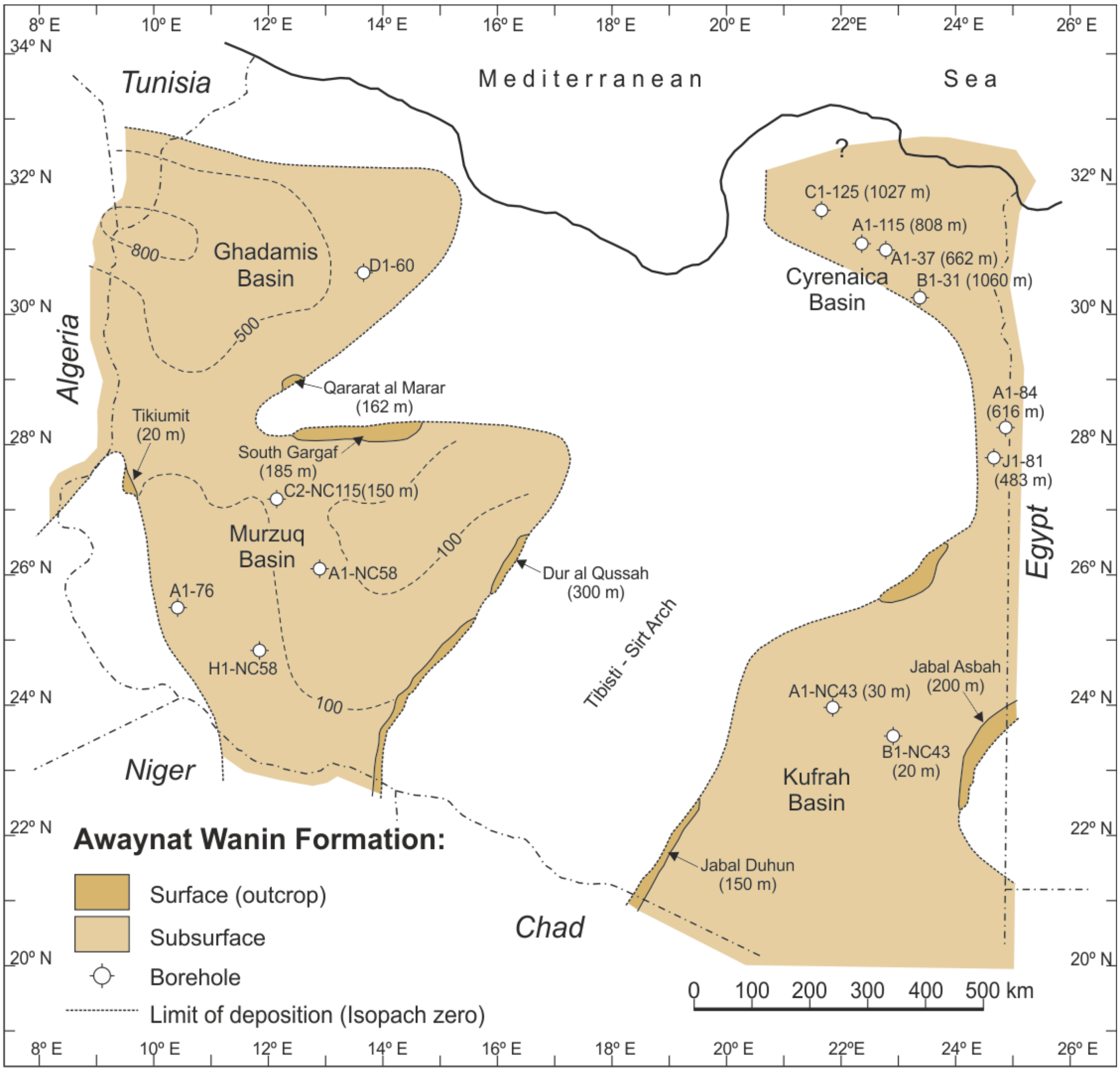


Figure 62.- Outcrop and subsurface extents of the Awainat Wanin Formation in Libya. Modified from Hallett (2002).

val becomes more shaly and thins westwards (Aziz, 2000; López, 2010).

On the basis of their brachiopod fauna, Mergl and Massa (2000) dated the Awainat Wanin Formation as Eifelian to early Frasnian (middle – late Devonian). Palynological studies carried out with subsurface samples from wells in NC-115 block (Aziz, 2000) reported the presence of the diagnostic acritarch species *Veryhachium pannuceum* and *Unellium winslowae*, together with the miospore marker species *Spelaeotriletes lepidophytus* and *Dictyotrilletes fimbriatus*, indicating a late Devonian age for the Awainat Wanin Formation in this area. These data are in accordance with the work by Miles (2001), which in a more exhaustive study carried out in a number of samples from wells of the same NC-115 block, conclude a Givetian to Frasnian (middle to upper Devonian) age for the Awainat Wanin Formation.

The Awaynat Wanin Formation has been interpreted as the result of deposition in a delta complex, ranging from delta front to fluvial-distributary channel deposits (Vos, 1981). The delta front deposits are associated with progradational beach and marine shelf often subjected to reworking by tidal currents and storm waves. According to this author, palaeocurrent data suggest a NW direction. Sutcliffe et al (2000) recognized a number of cycles made of shoreface, distributary channel and intertidal sequences, and Blanpied and Rubino (1997) defined nine tidal and wave-dominated transgressive high-stand sequences.

The Awaynat Wanin Formation crops out in the borders of the Murzuq Basin (Fig. 62). In the Tikiumit area, western Murzuq basin, a 20 m thick succession of ferruginous sandstones with silty and calcareous stringers has been reported. Bellini and Massa (1980) reported a 147 m thick section of shales, siltstones and sandstones, containing brachiopods and ferruginous oolites at Gour Iduka, in the northern Murzuq boundary. Awainat Wanin strata crops out forming a continuous belt in the eastern border of the basin, whith thicknesses ranging between 100 and 300 meters. In the subsurface the Awainat Wanin Formation has been recognized across the whole of the Murzuq Basin. All the wells in NC-115 and NC-186 penetrated the Awainat Wanin Formation. The formation is widely recognized in the subsurface of the Ghadamis Basin, as well as in the Kufrah and Cyrenaica basins (Fig. 62).

Some wells in NC-115 reported oil seems in the Awainat Wanin Formation, mainly in the BDS interval, but the formation is considered to have a generally very poor reservoir quality, except in some areas close to the Tihembokah high (Echikh, 1998). In the Ghadamis Basin the formation contains hydrocarbons.

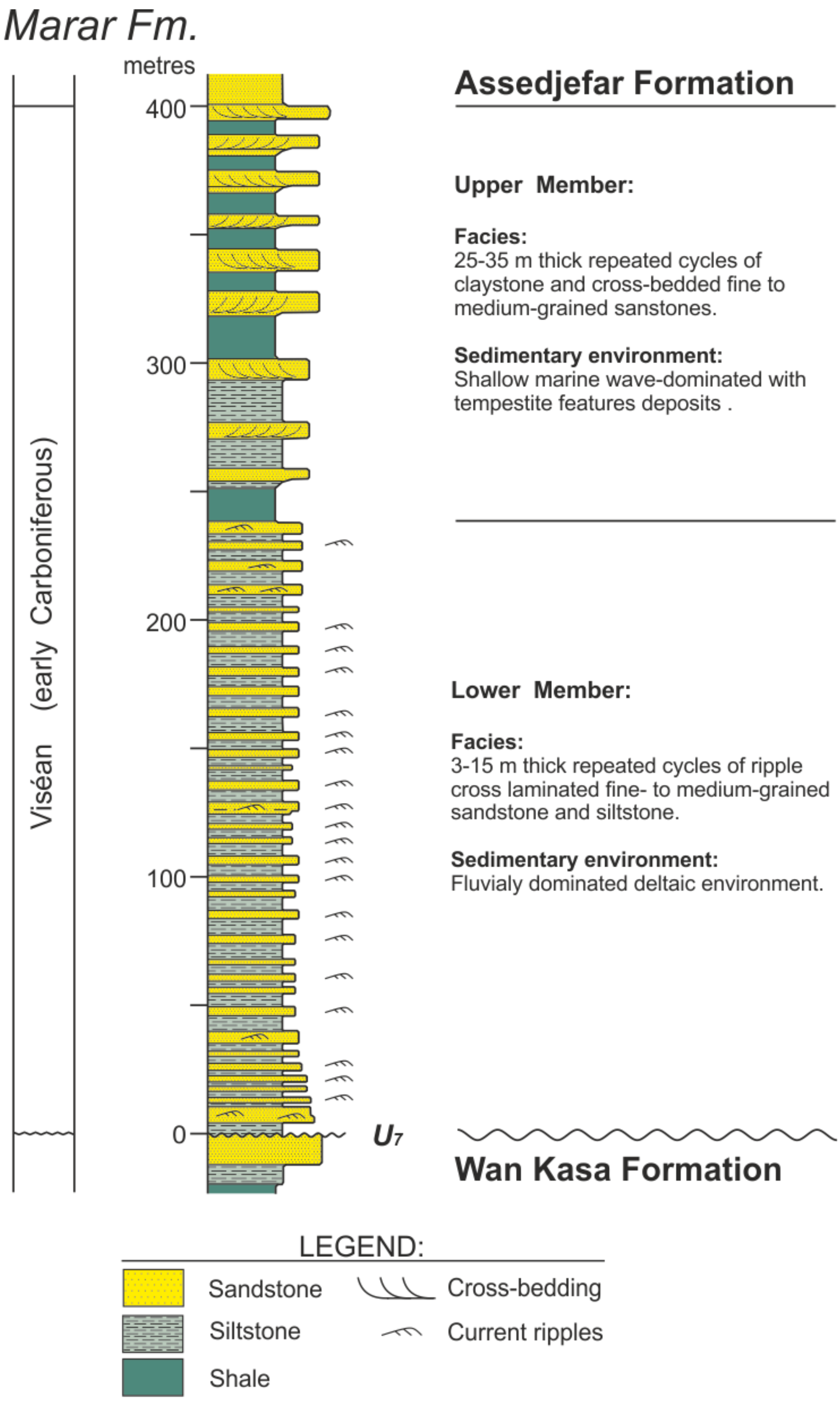
3.2.12. Marar Formation

The Marar Formation was first defined by Lelubre (1948) for a Carboniferous sequence cropping out at Qararar al Marar, in the Ghadamis basin, where a type section was proposed, and later the term was used by Collomb and Heller (1959) for the western Murzuq Basin. It could be considered equivalent to the Manarf Vella sandstone Formation described by Collomb, Bretizel and Heller (1958) in the subsurface of block NC49. The Mararar Formation unconformably overlies the older Devonian sequences. The top is conformable with the Assedjefar Formation. In the earlier works no type section was proposed, however Collomb (1962) provided a general description from the type area. According to this author, the Mararar Formation is a 400 meters thick cyclic, coarsening upwards succession (Fig. 63) consisting in about fifty staked thinning cycles made up of fine-grained sandstones, siltstones and silty claystones. The Formation contains abundant marine fossils and it is capped by thinly bedded limestones with *Collenia*, a fossil cyanobacteria that form a particular type of large-sized stromatolites (Fig. 64).

Based on the cycle’s thickness and the sandstone grain size, Gundobin (1985) divided the Marar Formation in two members (Fig. 63) The lower member consists of about 35 to 40 thinning upwards cycles 3 to 15 m thick each. The cycles are made by the succession of five intervals, from bottom to top are: 1) A basal interval of fine-grained cross-bedded sandstone, often conglomeratic at the base, sometimes with carbonate concretions and containing abundant marine and transitional brachiopod and pelecypod fossil remains. 2) An interval of interbedded sandstone, micaceous silty claystone and claystone. 3) Green claystone to micaceous silty claystone. 4) Green claystone, and 5) Dark gray to black claystone. The upper member is mainly sandy and it comprises nine thining upwards cycles, 25 to 35 meters thick each formed by sandstones, siltstones and silty claystones. The sandstones are medium- to fine-grained display hummocking cross stratification and contain ferruginous oolites and ferruginous plant fragments attributed to *Lycophyte* as well as marine and transitional brachiopod and pelecypod fossil remains. The top of the upper member contains carbonate beds made up by *Collenia* agae stromatolites.

The Marar Formation contains a major fossil record including benthic invertebrates (brachiopods, pelecypods, gastropods, crinoids, bryozoans and rugosa corals), conodonts, foraminifera and phytoplankton (miospores and acritarchs).

A study of the fossil brachiopods has been carried out by Mergl and Massa (2000). According to these authors in the northern Murzuq basin the sandstones of the lower part of the Marar Formation contain the chnetid *Saharonetes saharensis*, the lingulid *Wadiglossa* and the productid *Dictyoclostus*



Upper Member:

Facies:
25-35 m thick repeated cycles of claystone and cross-bedded fine to medium-grained sanstones.

Sedimentary environment:
Shallow marine wave-dominated with tempestite features deposits .

Lower Member:

Facies:
3-15 m thick repeated cycles of ripple cross laminated fine- to medium-grained sandstone and siltstone.

Sedimentary environment:
Fluvialy dominated deltaic environment.

Figure 63.- Stratigraphic type section for the Marar Formation. Modified from Gundobin (1985). Surface U_7 represents the basin-scale unconformity shown in Fig.19.

Figure 64.- Field view of a large-scale stromatolite constituted by Collenia red algae.

sp.; the middle part of the formation is characterized by the dominance of the spiriferids *Prospira platycosta*, *Brachythyris* sp., *Tylothyris* sp. and *Syringothyris* cf. *texta* associated with the terebratulid *Balanoconcha micropuncta*, and other brachiopods as *Antinoconchus lamellosa*, *Pleuropugnoides* cf. *pleurodon*, *Marginatia* sp., *Pustula* sp., *Schuchertella* sp., as well as gastropods, bivalves and crinoids. The upper part of the formation is characterized by the presence of *Dictyoclostus* cf. *semireticulatus* and the spiriferid *Phricodothyris* sp. These authors reported from outcrops of the western Murzuq Basin a fossil assemblage containing abundant *Prospira platycosta*, and *Syringothyris* sp. associated with other brachiopods as *Balanoconcha micropuncta*, *Antinoconchus lamellosus*, *Pleuropugnoides* cf. *pleurodon*, *Cleiothyridina* sp., *Marginatia* sp., *Pustula* sp. and *Schuchertella* sp., rare bivalves and corals. Another distinc assemblage consists of the presence of *Paurogastroderhynchus serdelesensis* (know in older works as *Septacamera*), *Septosyringothyris vautrini* (formerly *Histosirinx*) and *Setigerites*, sp. This assemblage has also been documented on the opposite eastern flank of the Murzuq Basin. The upper part of the Formation is characterized by the abundance of the syringothyyrid *Syringothyris* cf. *hannibalensis*, the productids *Fluctuaria*, *Argentiproductus* and *Libys*, the rhynchonellid *Cupularostrum*, and other benthic invertebrates as bryozoans, bivalves and corals.

According to Mergl and Massa (2000), fossil assemblage from the lower part of the Marar Formation are diagnostic of a late Tournaisian age, whereas the fossil assemblage from the upper part of the formation probably characterizes a Viséan age. Younger carboniferous strata have not been reported, because the gap related to the U_8 unconformity must include the uppermost Famennian and most of the Tournasian stages.

Milles (2001) carried out a palynological study based on samples from the subsurface of concession NC115. According to this author, the palynological fossil content of the Marar Formation is dominated by miospores with only sparse marine acritarchs, constituting a fossil assemblage typical of the early Carboniferous Viséan stage. This data agrees with previous studies largely based on macrofaunas.

The Marar Formation has been interpreted as the result of deposition in a delta environment. The lower member records deposition in a fluvial dominated delta system; the low levels of shell fragmentation and high number of articulated whole shells notated in the brachiopods and pelecypods from the finer sediments in this member indicate calm and fully marine conditions. On the other hand, the upper sandier member records deposition in a more energetic wave dominated delta system, where local storm reworking is recorded.

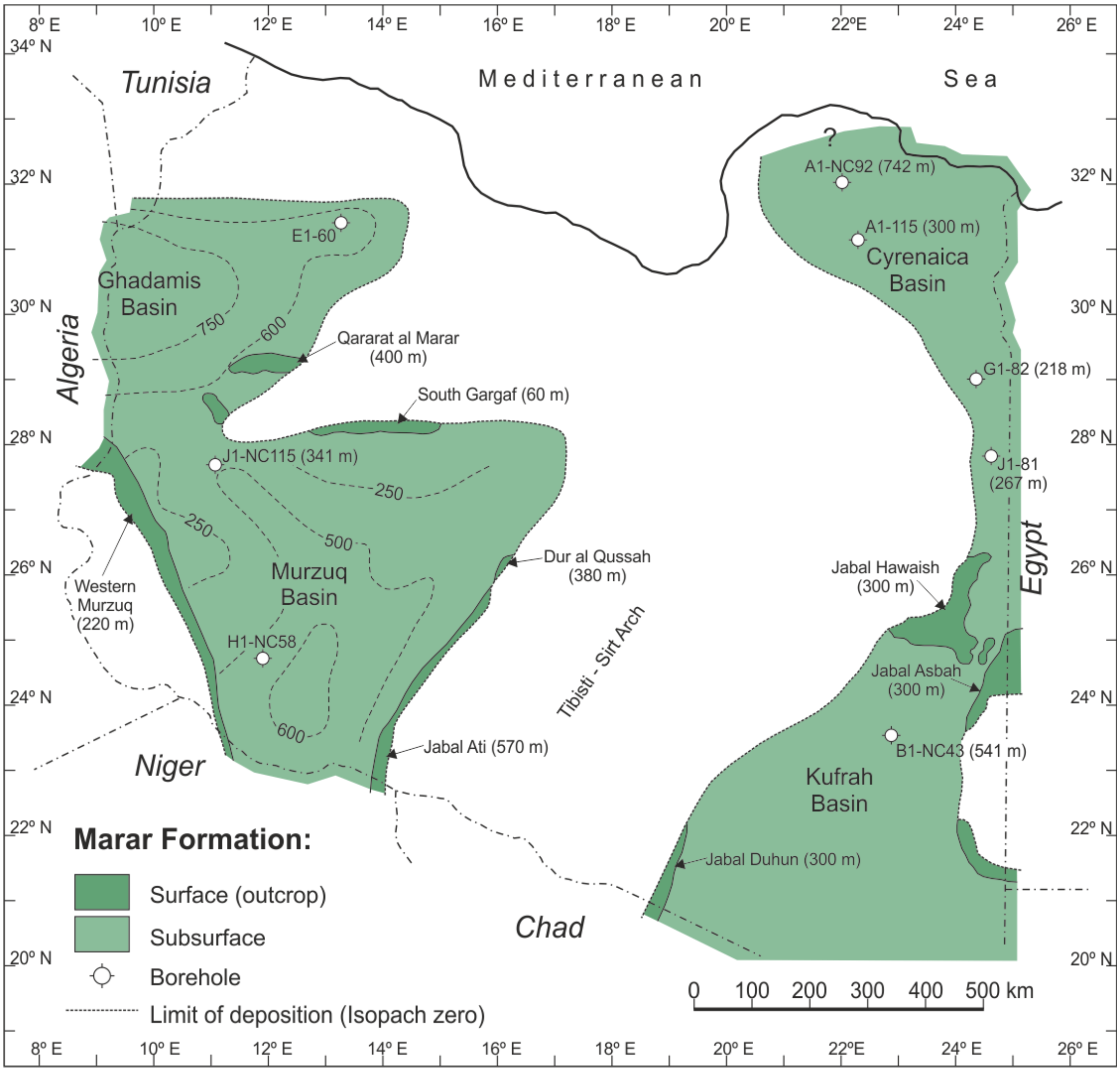


Figure 65.- Outcrop and subsurface extents of the Marar Formation in Libya. Modified from Hallett (2002).

The Marar Formation extents thorough most of Libya. It has been reported from outcrops and subsurface from the Ghadamis, Cyrenaica and Kufrah basins (Fig. 65). The former type area were Lelubre (1948) defined the formation is located northwestwards of the Gargaf uplift, in the Ghadamis Basin; most of the wells drilling the Ghadamis Basin penetrated Marar sequences reaching up to 800 m in thickness. In Cyrenaica basin a number of wells drilled the Marar Formation with thicknesses ranging from more than 150 m to 742 m (well A1-NC92). In the Al Kufrah Basin the Marar Formation is also penetrated by a number of boreholes (541 m in well B1-NC43) and large outcrops in the northern, eastern and western flanks of the basin exhibits early Carboniferous equivalent sequences (Fig. 65).

In the Murzuq basin the Marar Formation crops out forming extended belts along the basin boundaries. In the northern flank of the basin, a 200 km long outcrop extents in the Sabha – Idri area, where a 60 m thick Marar sequence forms the southern Gargaf. In the eastern flank of the Murzuq Basin outcrops of the Marar Formation form a continuous belt from the Dur al Qussah to the border of Niger, with thicknesses ranging from 380 to 570 metres. In the western boundary of the basin successions of the Marar Formation reaching around 200-250 m in thickness form a continuous belt extending from the border with Algeria, in the north, to the border with Niger, in the south (Fig. 65). In the subsurface the Marar Formation widely extends across the whole of the Murzuq basin, where a depocenter with thicknesses larger than 600 m exists. In a study of the subsurface of the NC115 block carried out by Aziz (2000), all the wells drilled in the block penetrated the Marar Formation, with thicknesses ranging between 154 and 226 metres. According to this author, in the subsurface of the NC115 concession the Marar Formation thickens southwards.

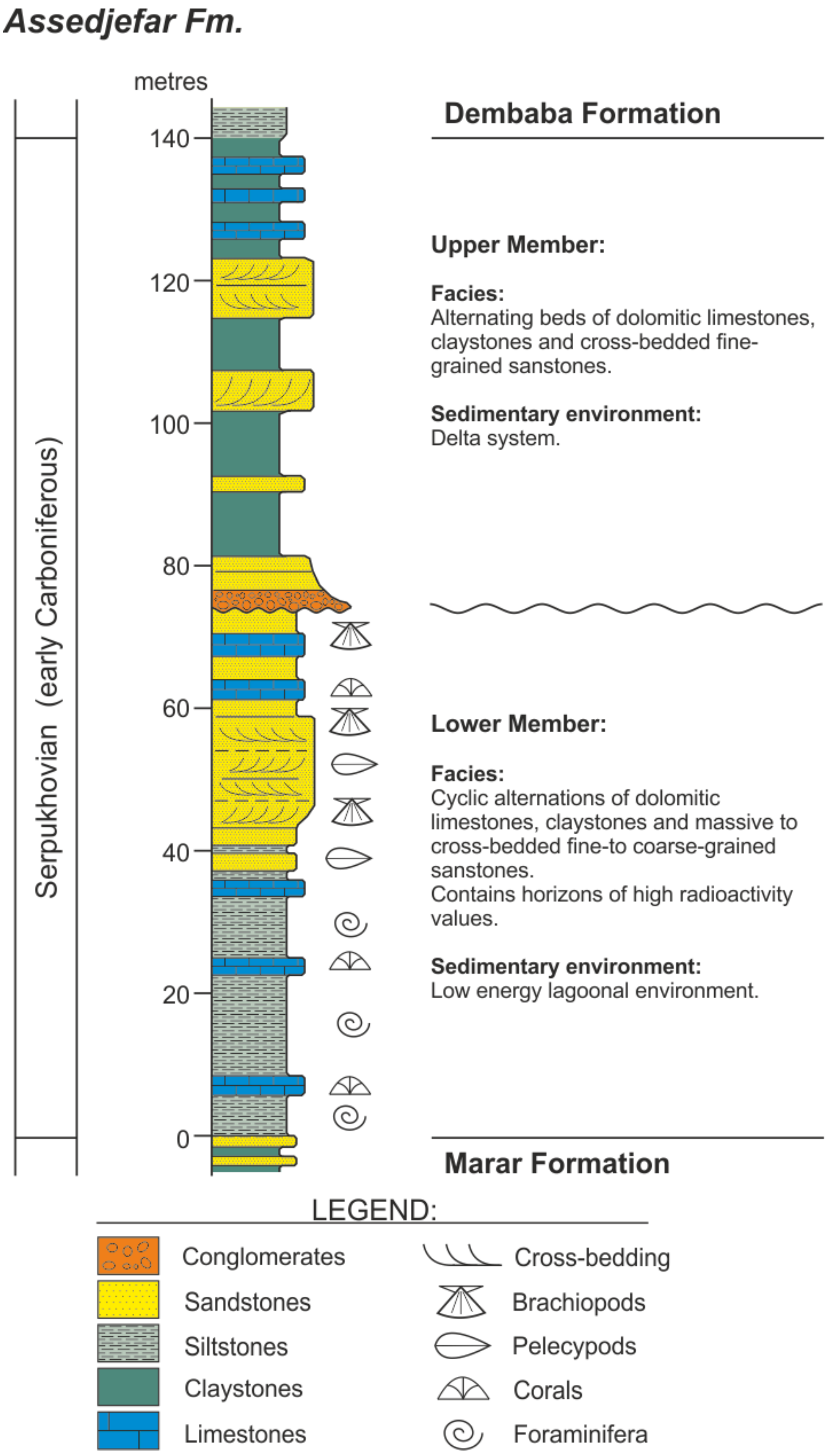
3.2.13. Assedjefar Formation

The name of the Assedjefar Formation was first proposed by Lelubre (1952) in western Libya and later, a type section was described by Collomb (1962) western of the Awaynat Wanin area. In the type area the bottom of the Assedjefar Formation is conformable on the underlying Marar Formation. The top is also a conformable surface passing to the overlying Dembaba Formation. In the type area the Assedjefar Formation shows rapid lateral variations, from a sandy sequence dominated by coarse-grained, cross-bedded sandstones containing silicified fossil trunk remains in the east to a thinner grained shaly sequence in the west.

In the Awaynat Wanin type area Berendeyev (1985) proposed a 140 m thick Assedjefar type section consisting of two members separated by a local unconformity (Fig. 66). The lower member is up to 100 m thick and the overlying upper member is about 60 m thick, although locally it can reach up to 150 metres.

The lower member mainly consists of a number of cycles of fine- to coarse-grained, cross-bedded or massive sandstone, siltstone and dolomitic limestone. Occasionally the sandstones are poorly consolidated, gypsiferous and/or ferruginous and contain wood fragments. The upper member consists of thick marly intervals with interstratified sandstone and dolomitic wackstone and packstone beds. The Assedjefar Formation contains a number of horizons with anomalous high radioactivity values that El Hawat and Ben Rahuma (2008) attributed to the presence of volcanic ash within the sediments.

The Assedjefar Formation contains a rich fossil record including brachiopods, gastropods, pelecypods, bryozoans, corals and rare trilobite as well as foraminifera conodonts and phytoplankton. A review of the brachiopod fauna of the Assedjefar Formation has been carried out by Mergl and Massa (2000), these authors reported from the lower member of the formation a fossil assemblage constituted by the productids genus *Echinoconchus*, *Flexaria*, *Juresiana*, *Linoproductus*, *Striatifera*, *Productus* and *Gigantoproductus*; other brachiopods include *Schellwienella*, *Rugosochonetes*, *Pleuropugnoides* and *Syringothyris jourdyi*. According to the authors, the latter species is a marker fossil for the early Namurian throughout the whole Sahara (Legrand-Blain, 1970). The upper fossil-bearing member of the formation yielded a similarly rich benthic fauna of brachiopods including some genera already common in the lower member as *Linoproductus*, *Productus* and *Syringothyris* and new elements, of which the productids *Ovatia* and *Antiquatonia* are the most significant. On the basis of these data, these authors assigns to the lower Assedjefar member a Namurian (=Serpukhovian) age. However, based on the work by Berendeyev (1985), El Hawat and Ben Rahuma (2008) consider a Viséan age for the lower member, whereas the upper member is considered as Serpukhovian in age.



Upper Member:

Facies:
Alternating beds of dolomitic limestones, claystones and cross-bedded fine-grained sanstones.

Sedimentary environment:
Delta system.

Lower Member:

Facies:
Cyclic alternations of dolomitic limestones, claystones and massive to cross-bedded fine-to coarse-grained sanstones.
Contains horizons of high radioactivity values.

Sedimentary environment:
Low energy lagoonal environment.

Figure 66.- Stratigraphic type section for the Assedjeffar Formation. Modified from Berendeyev (1985).

A palynological study carried out by Milles (2001) with samples from the Assedjefar Formation in the subsurface of the NC115 concession highlights that the Assedjefar Formation include tops of *Tricidarisporites serratus* and *Spelaeotriletes owensi* in the upper part of the formation and the tops of *Densosporites variomarginatus*, *Radiizonates radiatus* and *Aratrisporites saharensis* in the lower part. The presence of abundant *Lycospora pusilla* in the middle part of the Assedjefar Formation suggests a middle Serpukhovian age. The oldest occurrence of *Schopfipollenites ellipsoides* is accurately constrained in western Europe as base of the Serpukhovian stage. The occurrence of this datum within the Assedjefar Formation suggest an age no older than Serpukhovian.

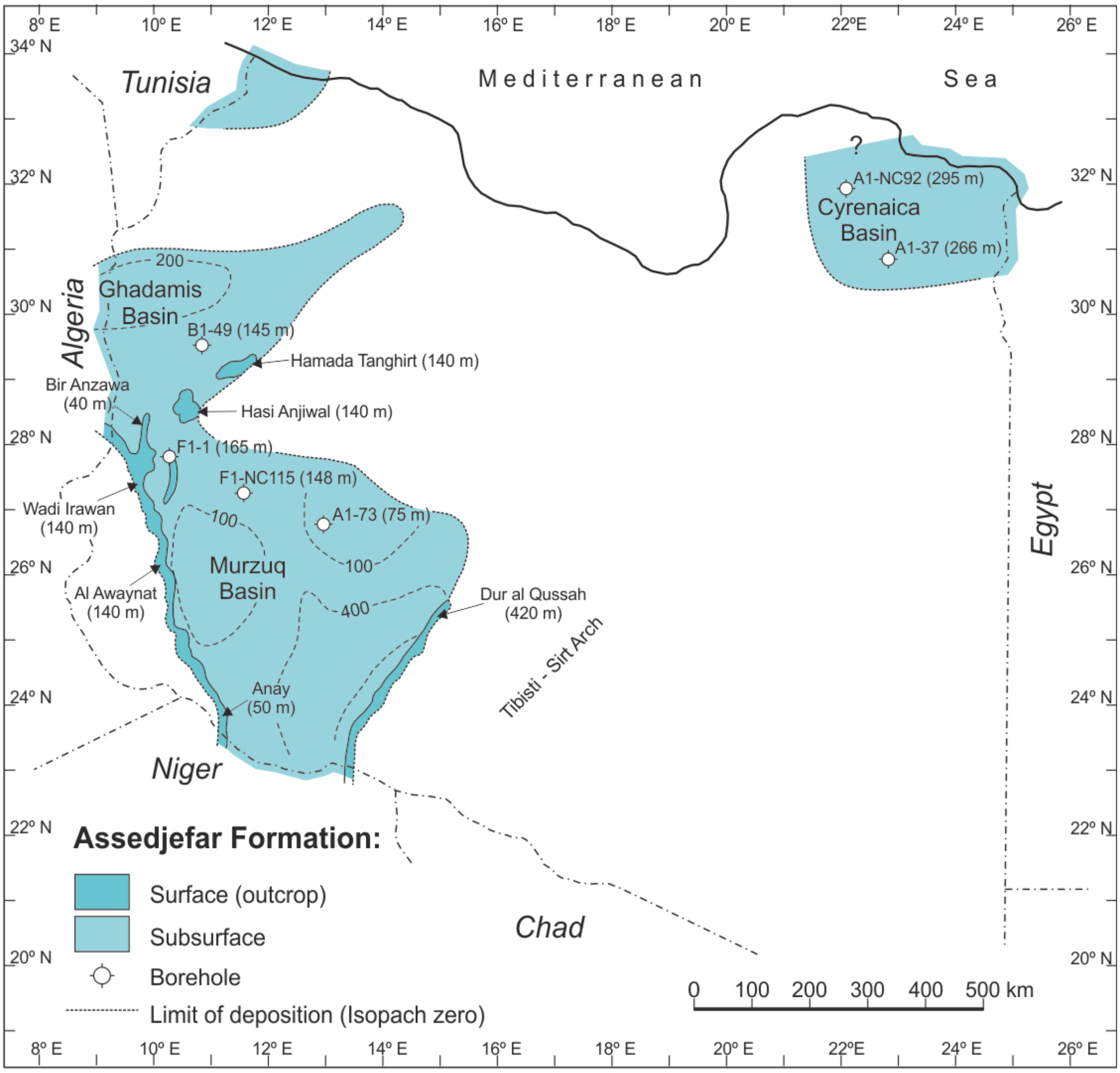


Figure 67.- Outcrop and subsurface extents of the Assedjeffar Formation in Libya. Modified from Hallett (2002).

Consequently, on the basis of their palynological content a Serpukhovian age is proposed for the Assedjefar Formation. This data is in agreement with the age proposed by Mergl and Massa (2000) based on the brachiopod record.

The Assedjefar Formation records deposition in a deltaic system, where the lower member is interpreted as the result of sedimentation in a low energy lagoonal environment, which must have been receiving siliciclastic input from the adjacent structural highs. Sedimentological analysis of the formation in the subsurface of the Murzuq Basin (NC115 concession) reported deposition of shoreface sandstones passing into more shaly facies westwards (Aziz, 2000).

Sequences of the Assedjefar Formation are reported from most of the Murzuq and Ghadamis basins, but their extent in the rest of Libya is poor. Apart from the above mentioned Murzuq and Ghadamis basins, the Assedjefar Formation has been penetrated in the northeast part of the Cyrenaica Basin; in northwestern Libya near the border with Tunisia and forming small inliers on the Sirt Arch (Fig. 67).

The formation has been mapped outcropping in the Hamadat Tanghirt type area, in the SE border of the Ghadamis Basin and the Hasi Anijwal, in the southern border. In both cases sequences around 140 m thick have been reported. In the subsurface it has been drilled only in the southern Ghadamis Basin where sequences more than 200 m have been penetrated.

In the Murzuq Basin the Assedjefar Formation crops out forming a continuous belt along their western flank, from Bi’r Anzawa in the north to Anay and the border with Niger in the south (Fig. 67). In the eastern flank a continuous belt of the formation crops out from Dur Al Qussah area to the border with Niger. The formation is not exposed in the northern border of the basin. In the subsurface the Assedjefar Formation extents across most of the Murzuq Basin. In a work about the subsurface of the N115 Concession (northern Murzuq Basin), Aziz (2000) reported that all the wells penetrate the Assedjefar Formation, with sequences ranging in thickness between 25 and 136 m, and Hallett (2002) reported thicknesses ranging between 165 m (well F1-1) and 75 m (A1-73).

3.2.14. Dembaba Formation

The Dembaba Formation is a dominantly carbonate unit which represents the younger Carboniferous marine strata preserved in the Murzuq Basin. The name was first introduced by Lelubre (1952) for describe a carbonate sequence drilled by the exploration well C1-49 and subsequently Collom (1962) described a 60 m thick Dembaba sequence in the Hamadat Tanghirt area. In general, within the Murzuq basin the Dembaba Formation shows from north to south thickness variations and lateral facies changes. The Dembaba Formation conformably overlies the Assedjefar Formation. Their top is conformable with the overlying Tinguentounine Formation although as the upper Carboniferous rocks are deeply eroded by the Hercynian uplift and erosion, this arrangement is rarely observable and generally the top of the Dembaba Formation is an erosive surface.

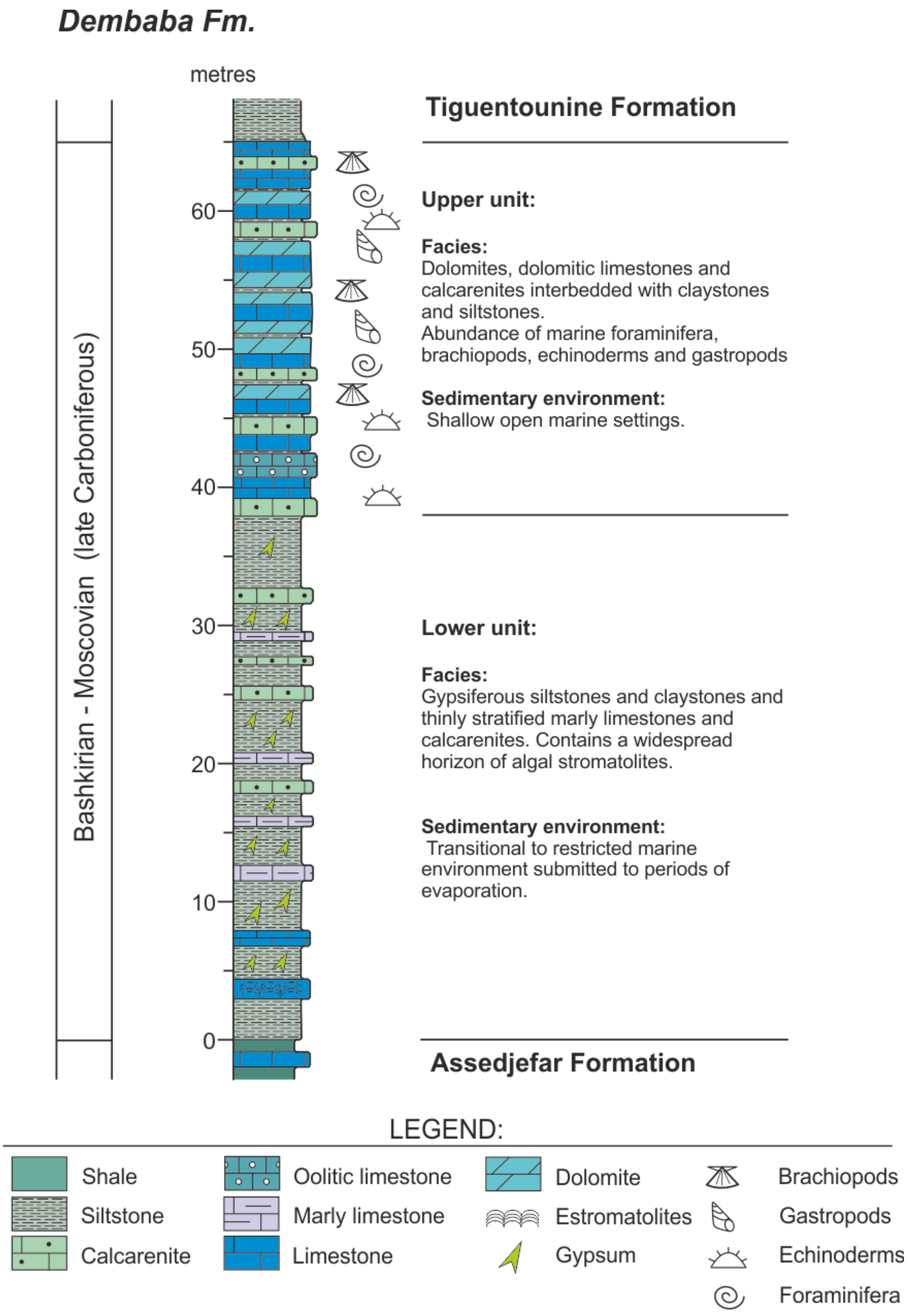
In the Qararat al Marar area, west of the Gargaf, the Dembaba Formation constitutes a 120 m thick sequence which could be divided into two units; a lower unit and an upper unit (Fig. 68).

The upper unit is made up of dolomites, dolomitic limestones and calcarenites interbedded with claystones and siltstones. Generally it contains a few mwters thick interval of sandy oolitic limestone rich in analcite, a mineral belonging to the zeolite group that is usually associated with alkaline lakes or the result of alteration of volcanic rocks.

The lower unit comprises gypsiferous claystone, siltstones and thin-bedded marly limestones and calcarenites. Near the base of the section a stromatolitic algal horizon, patchily developed but very widespread is present. Strata of the lower unit show evidences of brecciation related to the dissolution of gypsum and halite.

A rich fauna of brachiopods, echinoderms, gastropods and fusulinid foraminifers have been reported from the formation. The fossil record of the Dembaba Formation suggests a Bashkirian age for the lower unit and a Moscovian age for the upper unit (Vachard and Massa, 1984; Mergl and Massa, 2000; Aziz, 2000). However, it must be stressed that there are not agreement about the time span represented by the Dembaba Formation. Berendeyev (1985) extends the age for the upper unit up to the Gzelian, whereas in a palynological study based on subsurface samples, Miles (2001) suggests an age no younger than early Carboniferous for the Dembaba sequences within the NC-115. These variations in the time span covered by the Dembaba Formation could be related to the erosion of the upper part of the sequence by the above mentioned Hercynian erosive event.

The Dembaba Formation records deposition in a shallow marine setting. The lower unit is interpreted as the result of sedimentation in a transitional to



Upper unit:

Facies:
Dolomites, dolomitic limestones and calcarenites interbedded with claystones and siltstones.
Abundance of marine foraminifera, brachiopods, echinoderms and gastropods

Sedimentary environment:
Shallow open marine settings.

Lower unit:

Facies:
Gypsiferous siltstones and claystones and thinly stratified marly limestones and calcarenites. Contains a widespread horizon of algal stromatolites.

Sedimentary environment:
Transitional to restricted marine environment submitted to periods of evaporation.

Figure 68.- Stratigraphic type section for the Dembaba Formation. Modified from Roncevic (1984).

restricted marine environment subject to occasional periods of evaporation, gypsum and halite precipitation and stromatolite growth, with minor input of fine-grained clastic rocks. The upper unit records deposition in shallow although open marine conditions. In general, the Dembaba Formation display lateral facies variations from the south to the north. Southwards it records more restricted and littoral environments, whereas northwards it characterizes a shallow open marine setting.

The Dembaba Formation widely extent across the subsurface of Murzuq and south of Ghadamis basins, but it is absent in Kufrah, north of Ghadamis and most of Cyrenaica basins (Fig. 69).

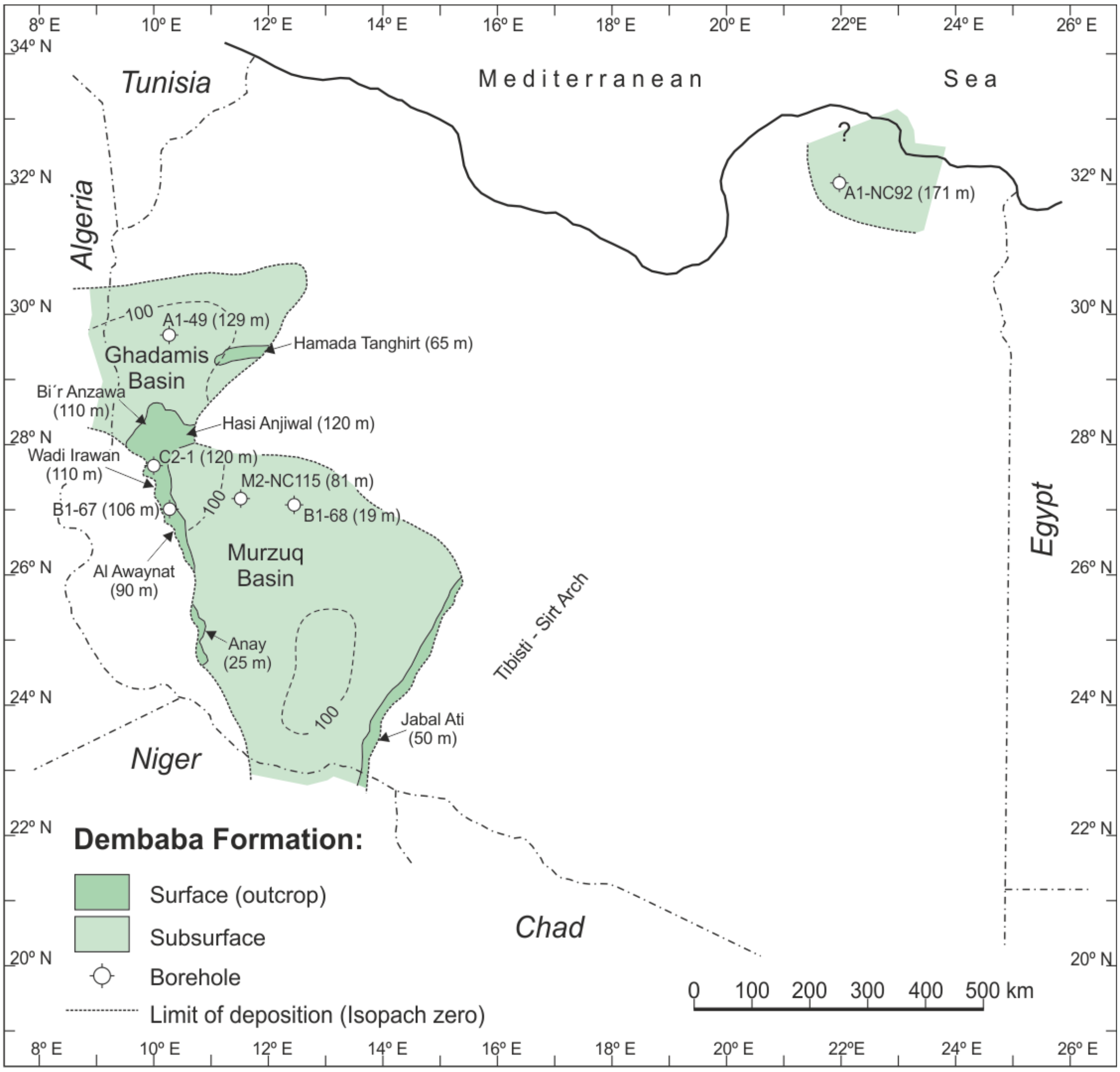


Figure 69.- Outcrop and subsurface extents of the Dembaba Formation in Libya. Modified from Hallett (2002).

In the subsurface of the Murzuq Basin the Dembaba Formation has been penetrated by many wells, with thicknesses ranging from 120 m in the C2-1 well to only 19 m in well B1-68 (Fig. 69). The Dembaba Formation largely outcrops on the flanks of the Murzuq Basin. West of the Gargaf high the formation crops out in the Qararat al Marar, Hasi Anjiwal and Bi’r Anzawa areas, where it averages 120 m in thickness. In the western margin of the Murzuq basin a belt of outcrops of the Dembaba Formation can be mapped, from Tikiumit to the border with Niger. In this limit the formation thins from 110 m at Wadi Irawan to 25 m at Anay. In the eastern flank of the Murzuq Basin the formation has been mapped forming a continuous belt from Dur al Qussah to the southern border with Niger; in this flank Klitzsch (1966) reported a 50 m thick Dembaba sequence in the Jabal Ati area.

3.2.15. Tiguentounine Formation

In the Murzuq basin, the Tiguentounine Formation represents the younger palaeozoic sequences recording deposition before the Hercynian uplift and the subsequent erosion of most of the African craton. It constituted a regressive unit which could be widely recognized in north Africa. These rocks occur widely in Algeria where they were first defined by Kilian (1931), as the Continental Post-Tassilien Group, and later subdivided by de Lapparent and Lelubre (1948) into the Tiguentounine, Zarzaitine and Taouratine formations. These authors defined a 80 m thick Tiguentounine type section in eastern Algeria. In Libya the formation crops out in the B'ir Anzawa area, in the northern flank of the Murzuq basin, were a 23 m thick type section has been proposed (Fig. 70). The Tiguentounine Formation rest conformably on the Dembaba Formation. Their top is an erosive surface (U_9 in Fig. 70) which is related to the main Hercynian tectonic phase. As a consequence of the erosive nature of their top, the Tiguentounine Formation displays wide thickness variations.

In the Libyan B'ir Anzawa area the section consists of red and greenish gypsiferous siltstones and dolomitis marls containing a 6 m thick bed of massive evaporites and thin beds of fine-grained sandstones (Fig. 70). The massive evaporites are pink coloured gypsum and anhidrite. The Tiguentounine Formation has been interpreted as the result of deposition in restricted marine lagoonal or non-marine environments. In the Algerian type area the Tiguentounine sequence beguines with a basal interval containing shallow marine ostracods, but in general the fossil record supplied by the Tiguentounine Formation is scarce an mainly constituted by palynological remains. Protic (1984) assigned a late Carboniferous age to the Tiguentounine Formation cropping out in the borders of the Murzuq Basin; however, palynological data supplied by wells in northwestern Murzuq Basin suggests that it extends into the early Permian. Based on a palynological study of subsurface samples from the NC115 concession, Miles (2001) extents the time span of the Tiguentounine Formation up to the Tatarian stage (late Permian).

The Tiguentounine Formation crops out along the eastern border of the Murzuq Basin forming a continuous belt from western of Dur al Qussah to the border with Niger (Fig. 71). In this area the formation is constituted by thick sequences of continental sandstones, although their age has not been suitably established. The formation crops out also in Bir Anzawa area, in the northern border of the basin. However, it has not been recognized outcroping in the Gargaf nor the western border of the Murzuq Basin where the Dembaba Formation is overlain directly by the Triassic sequences (Hallet, 2002).

The Tiguentounine Formation has been reported from the subsurface in most of the Murzuq wells. It has been penetrated in northern Murzuq by wells of concessions 67, 73 and NC115, reaching up to 533 m in thickness in well

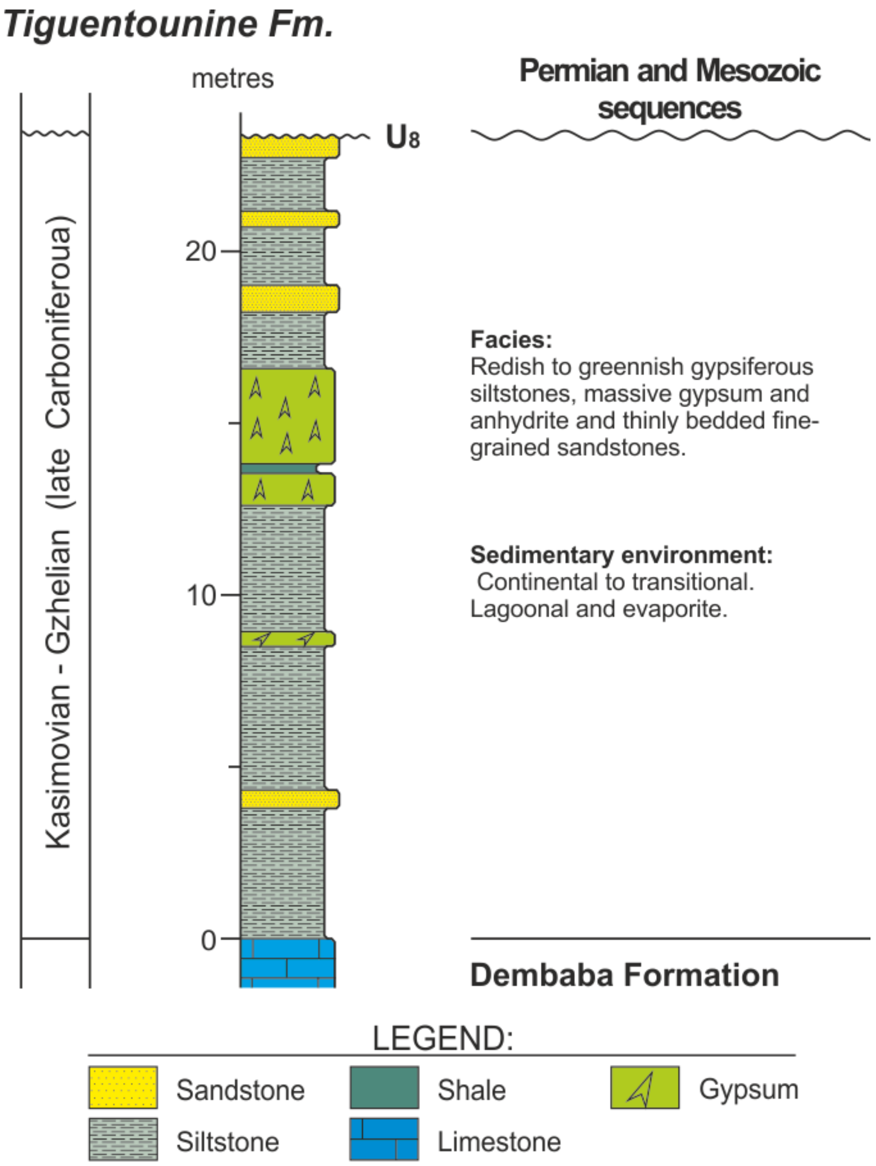


Figure 70.- Stratigraphic type section for the Tiguentounine Formation. Modified from Roncevic (1984). Surface U_8 represents the Hercinian basin-scale unconformity shown in Fig.19.

A1-73. Further south, in the central Murzuq Basin, the Tiguentounine Formation has been drilled by the Braspetro wells, where the top of the sequence has been dated as early Permian. In the subsurface the formation extends southwards onto the border with Niger (Hallet, 2002).

In the Ghadamis Basin Tiguentounine sequences have been reported in outcrops and the subsurface from their southwestern part, where thicknesses of about 70 and 100 m have been penetrated by wells B1-49 and A1-49 respectively. In northeast Libya similar continental facies dated by palinology as

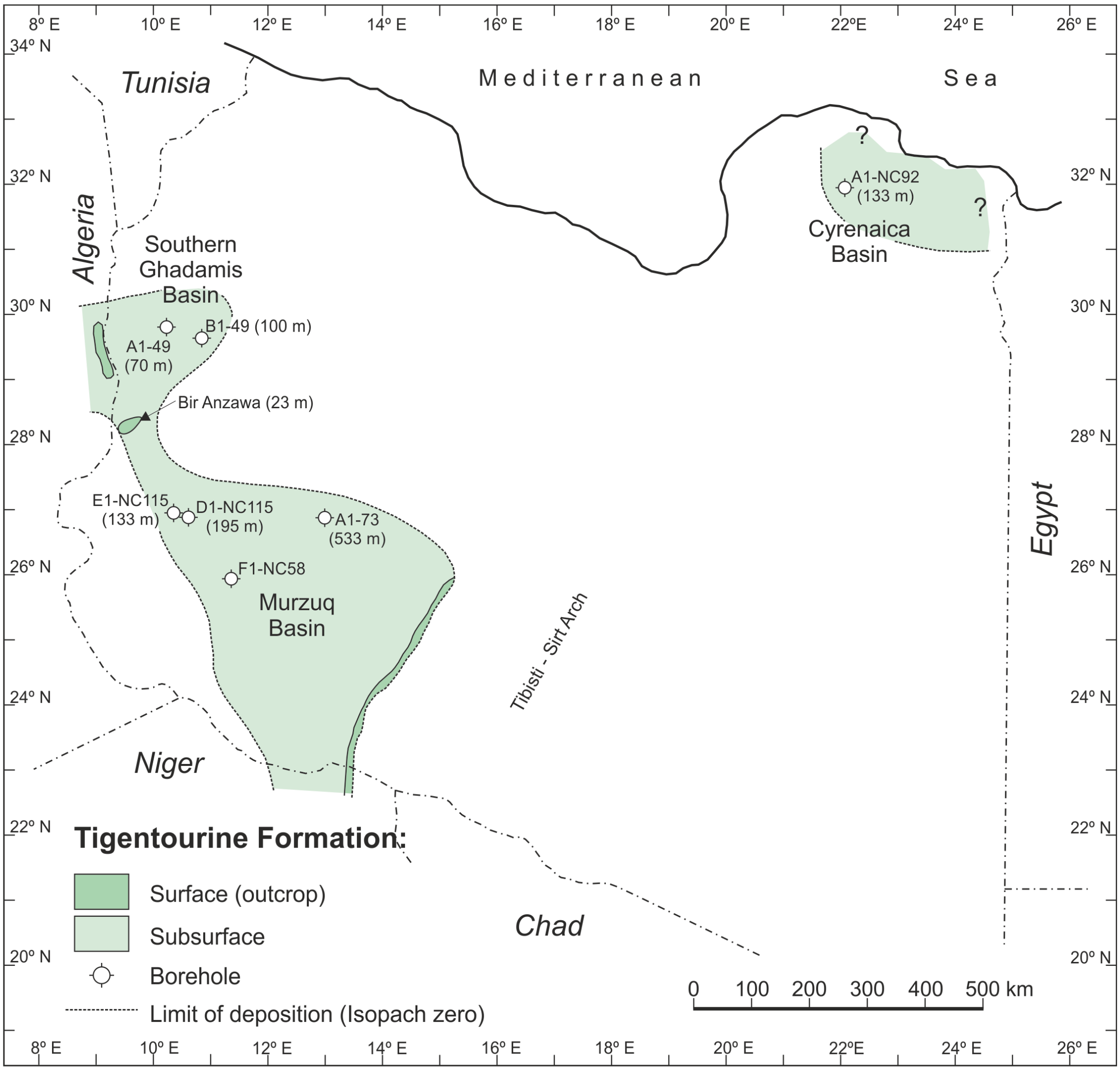


Figure 71.- Outcrop and subsurface extents of the Tiguentounine Formation in Libya. Modified from Hallett (2002).

Gzelian to Asselian in age and probably equivalent to the Tiguentounine Formation have been drilled by wells A1-NC92 and A1-19.

The Tiguentounine Formation has not been reported either at outcrop or in wells in the Kufrah Basin.

3.3. PALAEOZOIC SEQUENCE STRATIGRAPHY:

The Palaeozoic sedimentary infill of the Murzuq Basin have been synthesized by Van Hoeflaken and Dardour (2008) as made by the superposition of five 2th order sequences, each one bounded by major basin-scale unconformities; there are: 1) Middle Cambrian to early Ordovician sequence, 2) Late Ordovician to Silurian sequence, 3) Early Devonian sequence, 4) Late Devonian sequence, and 5) Carboniferous sequence. Each sequence is made by a number of lithostratigraphic units.

In this work, we take the above mentioned sequential subdivision although with some small specifications and clarifications, and our lithostratigraphic subdivision proposed in figure 19. According to this, we proposed the following 2th order sequential organization for the Palaeozoic infill of the Murzuq Basin:

a) Middle Cambrian – middle Ordovician sequence
b) Late Ordovician – Silurian sequence
c) Early Devonian sequence
d) Middle – late Devonian sequence
e) Carboniferous – early Permian sequence

a. Middle Cambrian – Middle Ordovician sequence:

This sequence includes all the pre-glaciar detrital deposits that were accumulated as major sand sheet under similar environmental conditions (fluvial, transitional and shallow marine settings). Deposition of these sediments took place on a broad continental shelf located a high altitude in the northern margin of Gondwana. The sequence is made by the Hasawnah, Achabiyat and Hawaz formations (Fig. 19) which form part of the Gargaf Group defined by Burollet (1960). The basal boundary of the sequence is the Pan-African unconformity (U_0 in Fig. 19), and the top is made by the glaciar erosive surface (U_2 in Fig. 19) related with the late Ordovician glaciation. This glaciar-related erosive surface (U_2) is a major regional surface, clearly recognizable in seismic sections across the whole of the Murzuq subsurface as well as in outcrops, in the structural highs bounding the basin. However, there is not agreement about the nature of this surface; some authors refers to this unconformity as the Taconian unconformity (i.e. Van Hoeflaken and Dardour, 2008) because they associate the unconformity to the structural movements related to the Taconian orogeny, and considers that the glaciar erosion was subordinated and superimposed to the Taconian orogeny, shaping the former tectonic relief. Nevertheless, seismic evidences (i.e. Fig. 16) show as the erosive incisions of the palaeotopography are not controlled by faults or other tectonic structures, because this, mostly authors mainly consider this surface as a glacially-related erosive surface, in spite that locally faults and other tectonic structures could appears.

The lithostratigraphic units constituting this sequence crops out in the Atshan, Gargaf, Tiemboka and Tibesti highs bordering the Murzuq basin, and their type sections have been defined all in the Gargaf high.

b. Late Ordovician – Silurian sequence:

The late Ordovician to Silurian is a 2nd order sequence bounded by the glacially related unconformity (U_2) at the base and the Caledonian unconformity (U_5 in figure 19) at top. It comprises an early Hirnantian lowstand system tract, late Hirnantian to early Llandoverian transgressive shales and a late Llandoverian to Pridoli highstand and can be arranged in a glacial and a post-glacial succession.

It is made by the Melaz Suqran, Mamuniyat, Bir Tlacsin, Tanezzuft and Akakus Formations. Within this succession, the Melaz Suqran and Mamuniyat formations represent the glacial sequence, whereas the Bir Tlacsin, Tanezzuft and Akakus formations represent the post-glacial sequence (Van Hoeflaken and Dardour, 2008).

c) Early Devonian sequence

The basal boundary of this sequence is made by the Caledonian unconformity at the base (U_5 in figure 19) and the middle Devonian unconformity U_6 at top. This sequence is constituted by the Tadrart and Wan Kasa formations. Following the terminal Silurian Caledonian unconformity, the early Devonian Tadrart and Wan Kasa conformable formations represents a gradual sea-level rise over most of the north Africa craton during the Pragian-Emsian times (El Hawat and Ben Rahuma, 2008).The upper boundary of this sequence is conflictive; whereas some authors refer to it as representing a major sea level fall, geological mapping by Galecic (1984) and Jakovljevik (1984) in the Kufrah Basin, near of the Sudanese border, show an angular unconformity between the lower Devonian Wan Kasa Formation and the overlaying lower Carboniferous Marar Formation. Nowhere on these maps are sediments of middle or late Devonian age. On the other hand, Mergl and Massa (2000) present biostratigraphic data from a measured section in the western Murzuq Basin, showing the presence of Middle and Late Devonian aged Awaynat Wanin sediments which they describe as apparently conformably overlying the Wan Kasa Formation.

d) Middle - late Devonian sequence

The late Devonian sequence is only constituted by the Awaynat Wanin Formation. In the Murzuq basin the middle and late Devonian Awaynat Wanin succession represented a condensed section consisting in sandy facies and several local erosive unconformities that allowed the subdivision of the Awainat Wanin Formation into a number of cycles (see section 3.2.11).

Various authors (Collom, 1962; Echikh and Sola, 2000) demonstrated that at the end of the Emsiam (middle Devonian) western Libya was affected by extensive tectonism (the pre-Frasnian phase after Echikh and Sola, 2000) which led the uplift of blocks and a forced marine regression, and the subsequent erosion and peneplaination of these reliefs. Most of the Awainat Wanin sediments were deposited by a marine transgression on this peneplained surface (U_6 in Fig. 19). Transgression onto the eroded surface was gradual and some areas such as the Tiririne uplift in the Murzuq basin were not covered until Famenian times (Hallet, 2002). The Devonian sedimentary record ends with an erosional unconformity (U_7 in Fig. 19) so that the late Famennian and the Tournaisian strata are missing over most of western Libya (Massa, 1988; Echikh and Sola, 2000).

In this way, the middle – late Devonian sequence is bounded by two basin-scale erosive surfaces (U_6 and U_7) and represents the middle to late Devonian marine transgression and deposition onto the exposed peneplained surface existing at the middle Devonian times as a consequence of the middle Devonian tectonism.

e) Carboniferous – early Permian sequence

The Carboniferous to early Permian sequence is made up by the Marar, Assedjefar, Dembaba and Tiguentounine formations. Although Carboniferous strata largely crop out on the flanks of the Murzuq Basin, the subsurface development and extent of the Carboniferous rocks across the basin are still poorly known as the operating companies have focused primarily on the Ordovician and Devonian potential reservoir intervals (Echikh and Sola, 2000).

This sequence records deposition since Viséan (early Carboniferous) to Asselian (early Permian) times. It is bounded by two basin scale erosive surfaces: the basal unconformity U_7 related to the erosive phase at the Devonian-Carboniferous boundary, and the unconformity U_8 at top, related to the Hercynian tectonic phase.

The sequence represents the Carboniferous marine transgression and regression. It starts with deposition on the erosive Devonian-Carboniferous surface of the high stand Marar Formation followed by the Assedjefar and

Dembaba deposits, which record progradational depositional systems and ends with the regressive deposits of the upper part of the Dembaba and the Tiguentounine continental sediments. There are a general agreement about that the late Carboniferous to early Permian regressive trend was controlled by the Hercynian tectonism, which produced regressive trends, emersion and continental deposition forming thick fluvial and lacustrine sequences in most of north Africa between the Hercynian uplift and the middle Cretaceous marine transgression. In the Murzuq Basin the uplifted highlands were submitted to erosion, and most of the Permian deposits if deposited, were eroded.

4. SOURCE ROCKS

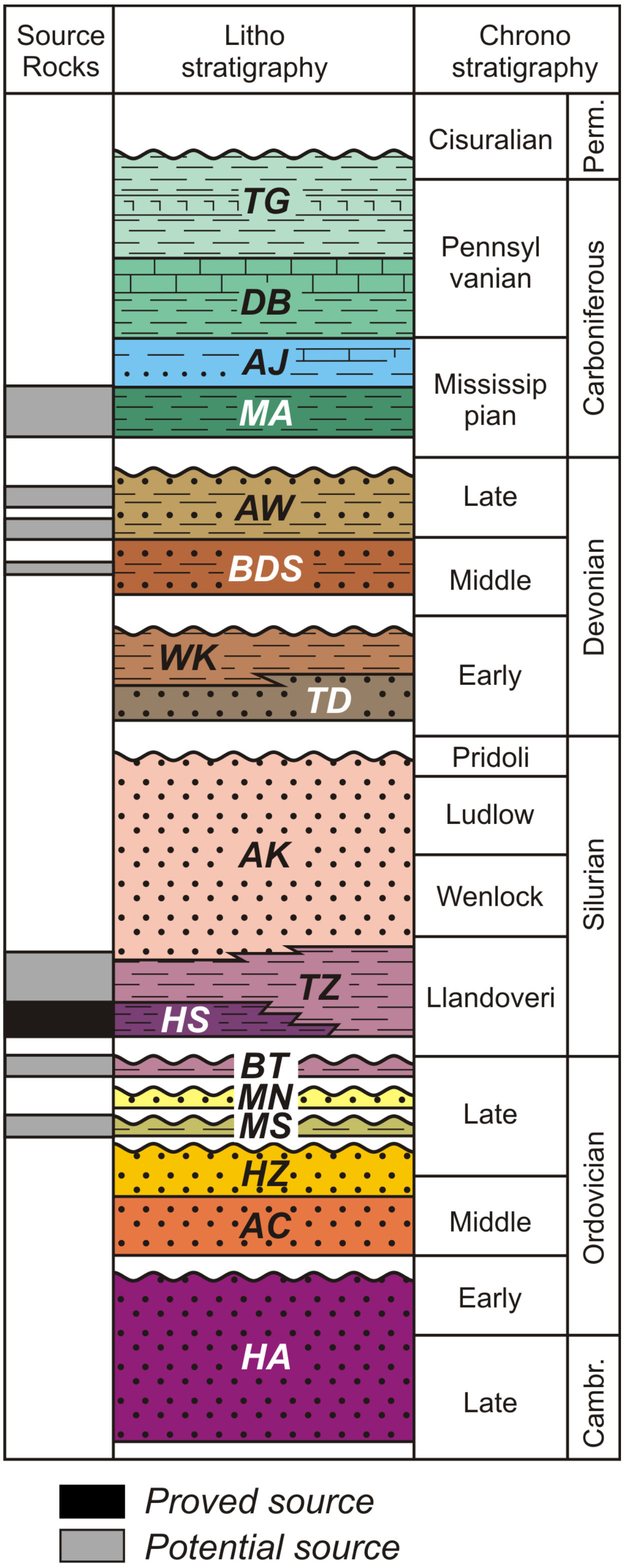


Figure 72.- Lithostratigraphic column of the sedimentary infill of the Murzuq Basin showing the potential source rock considered in this work.

Although the geochemical database from the Murzuq Basin is still limited, there are agreement that the four possible formations potentially able to generate hydrocarbons are, from younger to older, the early Carboniferous Marar Fm, the late Devonian Awainat Wanin Fm including the fine-grained interval of the Basal devonian Sandstones (BDS), the early Silurian Tanezzuft Fm and their basal Hot Shale Member (Echikh and Sola, 2000; Hallett, 2002; Lüning et al, 2003; Hall et al, 2012). Other lithostratigraphic units locally containing fine-grained organic-rich facies are the late Ordovician Melaz Suqran and Bir Tlacsin formations (Fig. 72). Although these units locally could reach moderate TOC contents, their significance as effective source rocks in Murzuq Basin has not been proven to date and their contribution to discoveries in the Murzuq Basin is speculative (Echikh and Sola, 2000).

However, there are agreement about that the most important source rock in the Murzuq Basin is the early Silurian basal Tanezzuft Hot Shale Member (Boote et al., 1998; Aziz, 2000; Echikh and Sola, 2000; Craik et al., 2001; Fello et al., 2006; Franco et al., 2012; Hall et al., 2012). In fact, there are two key studies regarding the regional distribution and quality of the source rocks in the basin; the first one is a five volumes REMSA's Report (Ismail et al, 2002; SOC, 2002 and NRG,

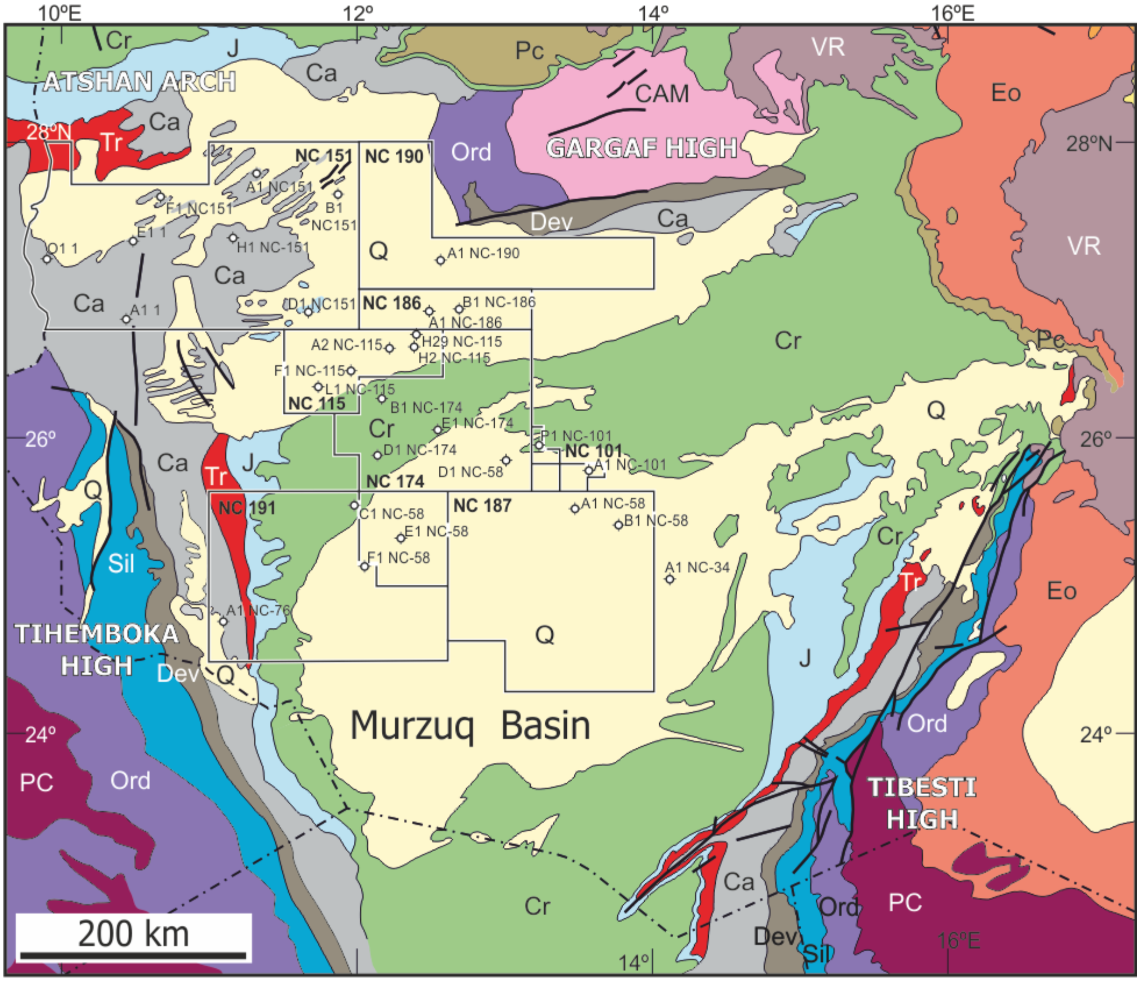


Figure 73.- Geological map of the Murzuq Basin showing the location of most of the wells sampled for the geochemical study, source potential and maduration by Ismail et al. (2002). Legend as in figure 9.

2002), the second one is a Report prepared by ROBERTSON for REMSA (Martin and Barnad, 2003), and both studies focused about the early Silurian Hot Shale Member, although they include complementary data about the other organic-rich units.

The first regional study (Ismail et al, 2002; SOC, 2002 and NRG, 2002) are supported by over 1200 samples derived from 79 wells distributed all over the basin (Fig. 73), the second one (Martin and Barnad, 2003) is based in a set of 209 samples from 8 wells of NC 186, NC 187 and NC 190 concessions. Screening TOC analysis, Rock-Eval Pyrolisis and Vitrinite Reflectance were measured in these sample sets.

4.1. SOURCE ROCKS

TOC content data over 950 samples are reported by Ismail et al (2002) and 174 by Martin and Barnad (2003). Analyses of samples were performed after their treatment with 10% hydrochloric acid by using a LECO S244 Carbon Analyser. Rock-eval pyrolisis were carried out on samples with more than 1% TOC, resulting in a data set of more than 300 samples in the SOC (2002) report and about 102 samples in the work by Martin and Barnad (2003). Rock-eval pyrolisis were performed by using a Rock-Eval VI Pyrolyser at Sirt Oil Company Laboratory in Brega.

A summary of TOC content for 174 samples after Martin and Barnad (2003) is shown in Table 2. According to these data and data supplied by SOC (2002), the Marar, Awainat Wanin and Tanezzuft formations have moderate to high TOC contents, and they are – “a priori” – potential source rocks; other units displaying moderate to high TOC contents which consequently could be considered as probable source rocks are the Bir Tlacsin and Melaz Suqran formations (Fig. 72). The Carboniferous Dembaba and Assedjefar formations resulted poorly sampled (1 and 5 samples respectively) because they have scarce fine-grained organic-rich facies. The measured TOC content for these facies ranges between 0.23 and 1.44 % (see Table 2), having their most frequent percentages between 0.25 and 0.60. The low proportion of shaly organic -rich facies and the relatively low TOC content of these facies suggest a low source potential for these formations.

Organic-rich shaly facies are more abundant in the early Carboniferous Marar Formation, were 91 samples were analysed. These samples have TOC values ranging between 0.35 and 8.68 as extreme values (see Table 2), but the most frequent values of TOC content are fewer than 4%, ranging between 1.0% and 2.0%; S2 values also are low, less than 6 mg HC/g rock, according to these data the Formation is considered as having poor to fair gas potential. The shaly Marar facies have mainly kerogen type III or IV and in rare cases type II/III kerogen, with Hydrogen indexes ranging between 200 and 300 mg HC/gTOC. Kerogen composition indicates a land plant-dominated organic contribution.

Although Marar shales are proven source for some oil and gas discoveries northwards of Murzuq Basin, in Ghadamis and Illizi basins, and the fact that locally some of Murzuq facies have high TOC contents (up to 8.68%), the Marar Formation is considered as having poor to fair gas potential, and their possible contribution as source rocks in Murzuq Basin remains uncertain. In some areas of the basin (e.g. in NC 115) they are immature and have not entered in the oil window (Aziz, 2000). According to this author the shaly facies of the Marar Formation probably had a better potential as source rock in the cen-

Table 2.- TOC values (%) and range of variation for a selection of 174 samples. From Martin and Barnard (2003).

Well	Unit	No. samples	TOC (%) max-min.
A1-NC 186	Tanezzuft Fm.	7	0.53 - 1.34
D1-NC 186	Marar Fm.	11	0.64 - 2.41
	Awainat Wanin Fm.	5	0.61 - 3.34
	Middle Devonian	2	0.75 - 0.92
	Tanezzuft Fm.	2	0.79 - 0.85
	Melaz Suqran Fm.	1	0.62
D3-NC 186	Melaz Suqran Fm.	7	0.37 - 0.81
E1-NC 186	Tanezzuft Fm.	3	0.47 - 0.65
	Bir Tlacsin Fm.	2	0.47 - 0.48
F1-NC 186	Dembaba Fm.	1	0.23
	Assedjefar Fm.	1	0.26
	Marar Fm.	13	0.52 - 8.68
	Awainat Wanin Fm.	3	1.18 - 1.94
	Middle Devonian	2	1.13 - 1.45
	Tanezzuft Fm.	16	0.41 - 23.28
	Bir Tlacsin Fm.	6	0.41 - 8.91
A1-NC 187	Marar Fm.	15	0.5 - 3.43
	Upper Devonian	4	1.31 - 1.78
	Tanezzuft Fm.	3	0.41 - 0.94
B1-NC 187	Assedjefar Fm.	4	0.42 - 1.44
	Marar Fm.	37	0.35 - 4.49
	Upp.-Midd. Devonian	4	0.29 - 3.46
	Tanezzuft Fm.	4	0.33 - 0.66
A1-NC 190	Marar Fm.	15	0.73 - 2.14
	Awainat Wanin Fm.	4	0.91 - 1.28
	Middle Devonian	1	0.93
	Tanezzuft Fm.	5	0.41 - 2.01

tre of the basin, were the formation is deepest buried, but there are not available data of this unit in the basin depocenter, and their source potential would be questionable (Fig. 72).

Similarly, the cyclic sedimentation which characterizes the late Devonian Awainat Wanin Formation contains abundance of shaly organic-rich facies. Up to 16 studied samples of fine-grained facies of the Awainat Wanin Fm, including four undifferentiated upper Devonian samples which could be attributed to the BDS member, have been studied. TOC analysis of the late Devonian Awainat Wanin samples show TOC contents ranging from 0.61 to 3.34% (Table 2), with the most frequent values between 0.80 and 1.30%. Hall et al. (2012) reported TOC values up to 6% and S2 up to 15 mgHC/g rock for the best samples. The shales of the Awainat Wanin Formation have similar or slightly better potential to the Marar Formation. They are, like the Marar shales, generally gas-prone, however, in some areas the Awainat Wanin Formation have fair to good oil potential and screening data by Hall et al. (2012) show that the more oil-prone shales having the richer TOC (up to 6.0%) and S2 (up to 15 mg HC/g rock) contain kerogen type II/III grading to type II kerogen. The Awainat Wanin kerogen composition is also fairly similar to the Marar Formation in that land plant debris is abundant, but in this case, with slightly greater algal content, notably acritarchs. As the Marar Formation, the Awainat Wanin source potential must be also questioned due to maturity considerations.

Up to 40 samples of the thick shaly Tanezzuft Formation have been analysed. Tanezzuft shales have reported TOC contents ranging from 0.33 to 3%, although mostly have less than 3.0% TOC and less than 10 mg HC/g rock of S2, and type III or II/III kerogen, with the better quality kerogen usually at the base of the formation. However, the vast majority of shales generally have less than 1% TOC so that the Tanezzuft shales generally have poor to fair potential for gas and minor oil generation. Locally the Tanezzuft Formation contains thin horizons where shales are good oil-prone source rocks, although not nearly as prolific as the basal Hot Shale Member. The difference in kerogen composition of the Tanezzuft Formation and the Hot Shale Member appears to be mainly in quantity rather than composition (Hall et al, 2012). The better quality Tanezzuft being towards the base and just above the Hot Shales where it is present. Interestingly many of the Tanezzuft shales with less than 1% TOC have acritarch -rich kerogens suggesting they have slight oil potential.

The analytical data confirms the early Silurian Hot Shales Member as the principal source rocks for the Murzuq Basin. The Hot Shales term refers to a black radioactive graptolitic shale facies that was accumulated as discontinuous lenses filling palaeotopographic lows on an erosive late Ordovician surface, where restricted water circulation and anoxic conditions suitable for preservation of organic matter could have existed. Samples of the Hot Shales Member have reported the highest TOC values, with TOC contents ranging from 2.0 up to 23.3% and with S2 values up to 100 mg HC/g rock. These data described the unit as a good source rock with fair source potential. However, it must be highlighted the discontinuous nature of the Hot Shales occurrence. The distribution of the Hot Shales in the northern and central parts of the Murzuq Basin, where a reasonable amount of subsurface data is available is currently well defined, but the Hot Shales distribution remains poorly known for the southern basin, where the available data are scarce.

Other dominantly fine-grained units locally containing diverse organic carbon content are the late Ordovician Bir Tlacsin and Melaz Suqran Formations. Eight samples of each unit have been analysed (Table 2). TOC contents ranging from 0.41 up to 8.91% have been measured in samples belonging to the Bir Tlacsin Formation, which normally displays values higher than 1%. Samples derived from Melaz Suqran Formation have lower TOC values ranging from 0.37 to 0.81%, in any case clearly less than 1 %. Both formations display a discontinuous distribution across the basin as they were deposited filling the lows of former palaeoreliefs related to the late Ordovician glaciation. Because their low TOC content and patchy features, the potential as source rocks of both formations must be considered as moderate to nil.

4.2. MADURATION, KEROGEN TYPE AND PETROLEUM POTENTIAL OF THE HOT SHALE MEMBER

The basal Tanezufft Hot Shales samples have reported the highest TOC values, with TOC contents ranging from 2.0 to 23.3%. Apart from these extreme values the most of the Hot Shales samples have TOC percentages raging between 3.0 and 15%. The organic-rich Hot Shales facies contain mainly Type II oil-prone amorphous kerogen and they are characterized by good pyrolisis-related hydrocarbon generative potential parameters such as S2 and Hydrogen index (HI). Hydrogen Index values range between 50 and 400, although most of the samples have values lowers than 175. Usually S2 values reach up to at least 60 mg HC/g rock and probably up to 100 mg HC/g rock for the best samples, both indicative of a rich source rock. According to Hall et al (2012), these HI and S2 values characterize an immature to early mature source rock, indicating their very good initial source potential for the Hot Shales. On the other hand, low HI and S2 values recorded in some Hot Shale samples (HI<80 and S2<2.5 – 3) characterize high overmatured samples or extensive kerogen degradation, probably due to deposition in an oxic/dysoxic water column, which causes a reduction in the amount of hydrogen-rich (oil-prone) organic matter, resulting in a reduced hydrocarbon generating potential for these samples.

Cross plots of hydrogen index versus oxygen index on a pseudo-Van Krevelen diagram for 123 samples with TOC contents higher than 1% derived from 10 wells drilled in concessions 76, NC58, NC101, NC151, NC174 and NC186 (Fig. 74) clearly classify most of the kero-

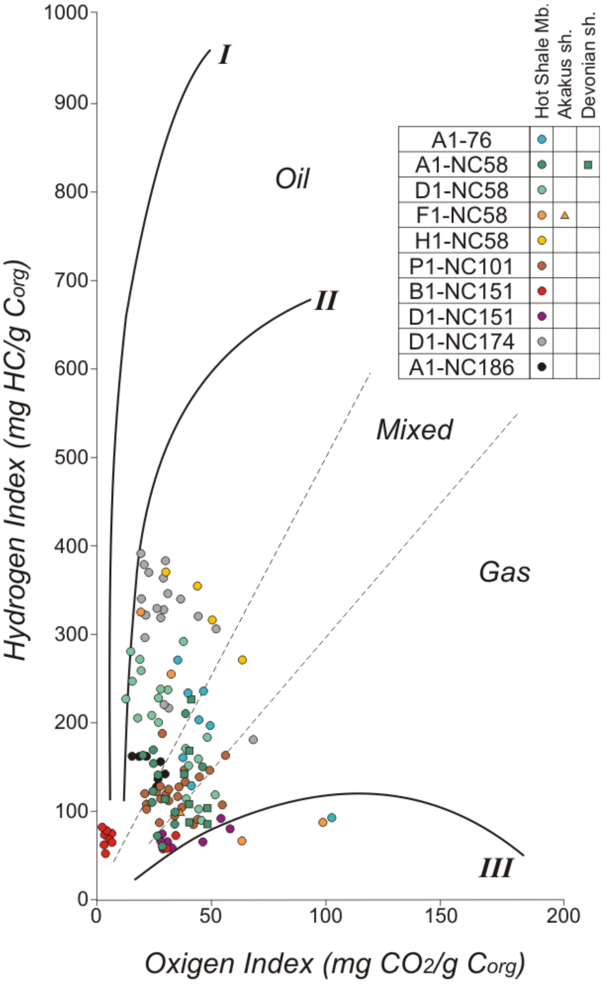


Figure 74.- Oxigen Index versus Hydrogen Index pseudo-Van Krevelen plot for a selection of 114 samples. From SOC (2002).

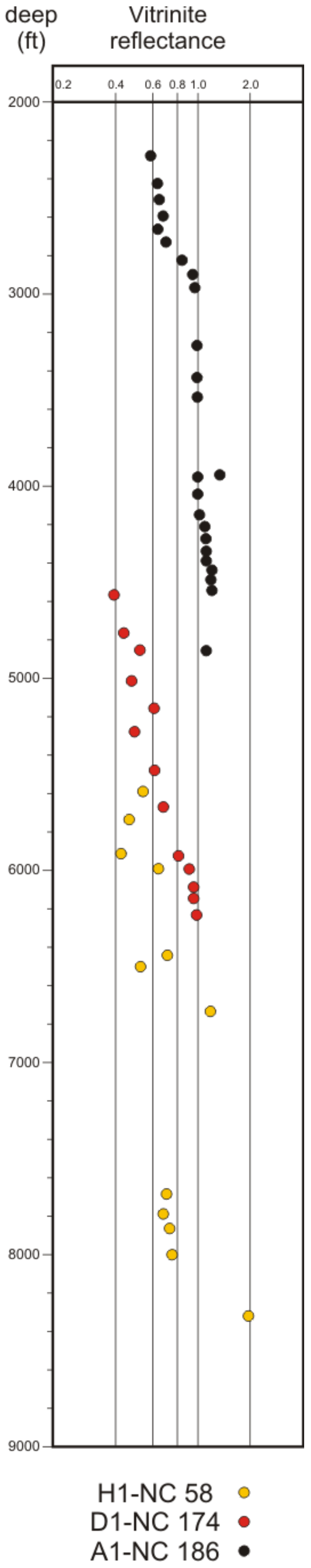


Figure 75.- Vitrinite reflectance vs. depth variation for wells H1-NC58, D1-NC174 and A1-NC186.

gen as predominantly type II oil-prone kerogen. Typically, the HI/OI ratios in the cross plots are scattered between the type II and type III maturation pathways, with few HI/OI ratios in either in the type I or type III zones. According to Ismail et al. (2002), the microscopic kerogen analyses as well as elemental analysis based Van Krevelen diagrams are in agreement with this assessment of the pyrolisis data.

Additionally, standard Rock-eval pyrolisis analyses supplied Tmax values. Tmax is directly stated in ºC units and it is considered as the temperature at which the top of the peak S2 occurs, consequently it is related to the degree of thermal maturity. Generally oil-prone clastic source rocks are mature and will generate oil at Tmax temperature range of 435 – 460 ºC. Tmax values higher than 460-470 ºC indicates overmature conditions for oil generation, and Tmax values lower than 450 – 460 ºC indicate inmature to early mature settings for oil generation.

According to the SOC (2002) report, Tmax values of the analysed Hot Shales samples are mostly in the main oil window (430-446º C range) and clearly increase with increasing depth. Nevertheless, few samples from NC58 and NC151 areas reported high Tmax values suggesting late maturity for oil generation. On the other hand, immature to early mature thermal maturity levels were indicated by low Tmax values in samples from west and southwest of NC187 area. The inferred Tmax maturity levels are in agreement with the other measured maturity parameters as vitrinite reflectance (Fig. 75) and spore colour index.

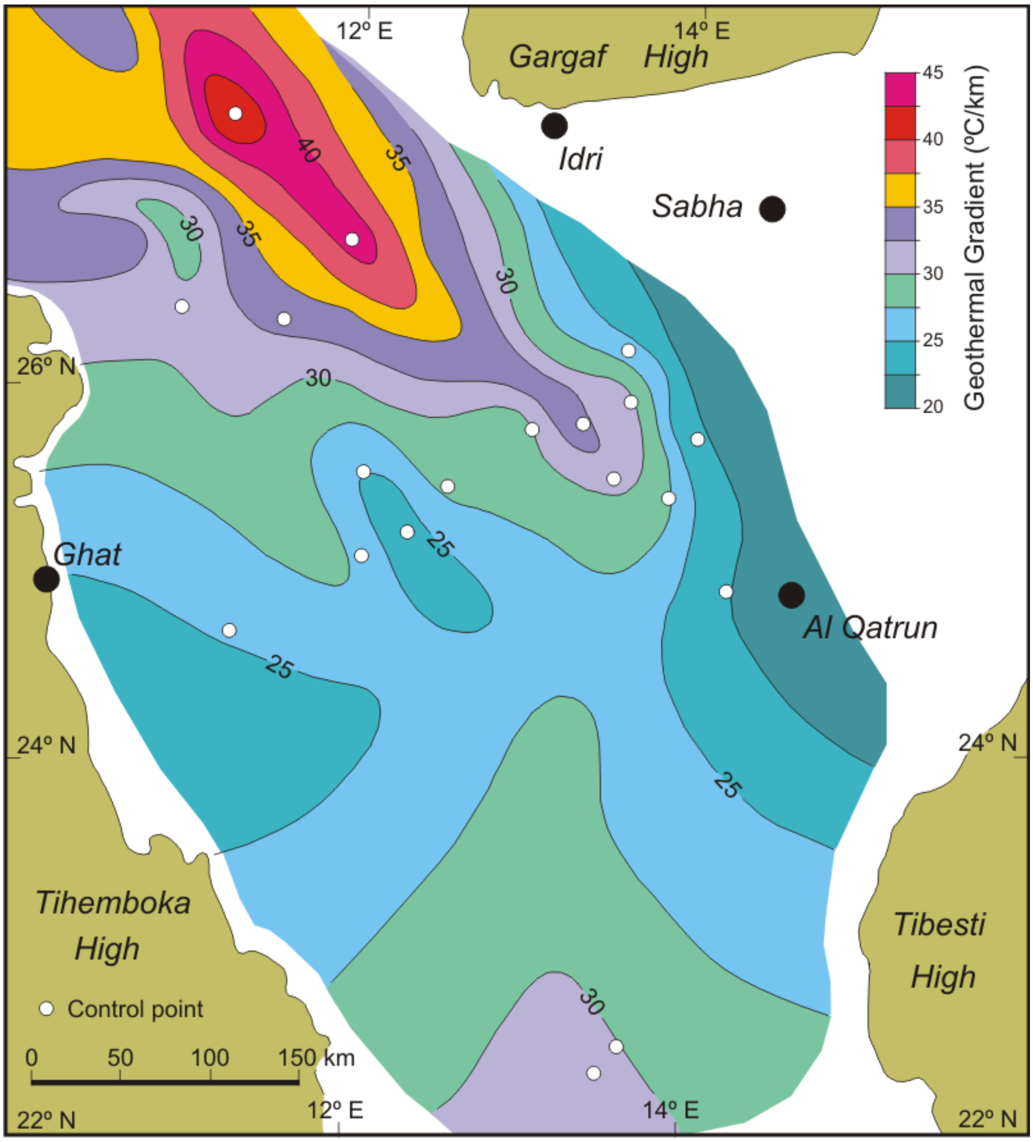


Figure 76.- Geothermal gradient (ºC/km) for the Murzuq Basin.

It is widely accepted that oil window is located in the range of vitrinite reflectance values between 0.5 %Ro and 1.4 %Ro, with the peak oil generation maturity between 0.8 and 1.2 %Ro. Figure 75 shows the increasing vitrinite reflectance values with depth for three wells (H1-NC58, D1-NC174 and A1-NC186). The vitrinite Ro increase vs. dept reflects different trends as a consequence of the different geothermal gradient across the basin (Fig. 76). Well A1 -NC186, located in the northern Murzuq Basin records the maximum increasing of Ro values with dept, whereas well H1-NC58, located in the central basin have the minimum Ro increasing vs. dept. This is in agreement with the Murzuq Basin geothermal gradient distribution. The great geothermal gradient, reaching more than 42.5ºC/km is recorded in the northern Murzuq Basin, whereas to the central basin the thermal gradient falls up to values lesser than

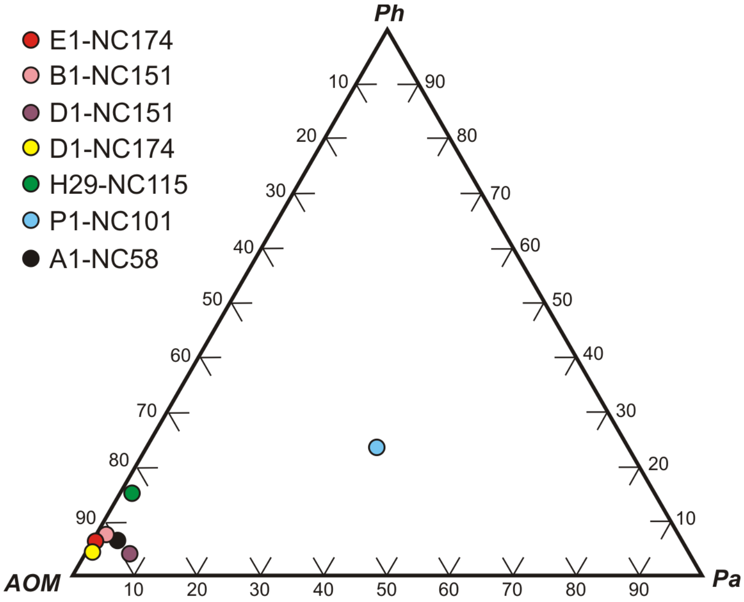


Figure 77.- Kerogen components ternary plot. **AOM** = % Amorphous Organic Matter; **Ph** = % Phytoclasts; **Pa** = % Palynomorphs. After Ismail et al. (2002).

22.5ºC/km. Southwards the thermal gradient displays a slight increasing trend. However, it must be highlighted that available subsurface data are scarce in this southern area.

Vitrinite reflectance data showed in figure 75 show as the most of the samples fall into the oil window (0.5 – 1.4 %Ro). Few samples (the shallower of the central basin D1-NC174 and H1-NC186 wells) fall into the inmature field

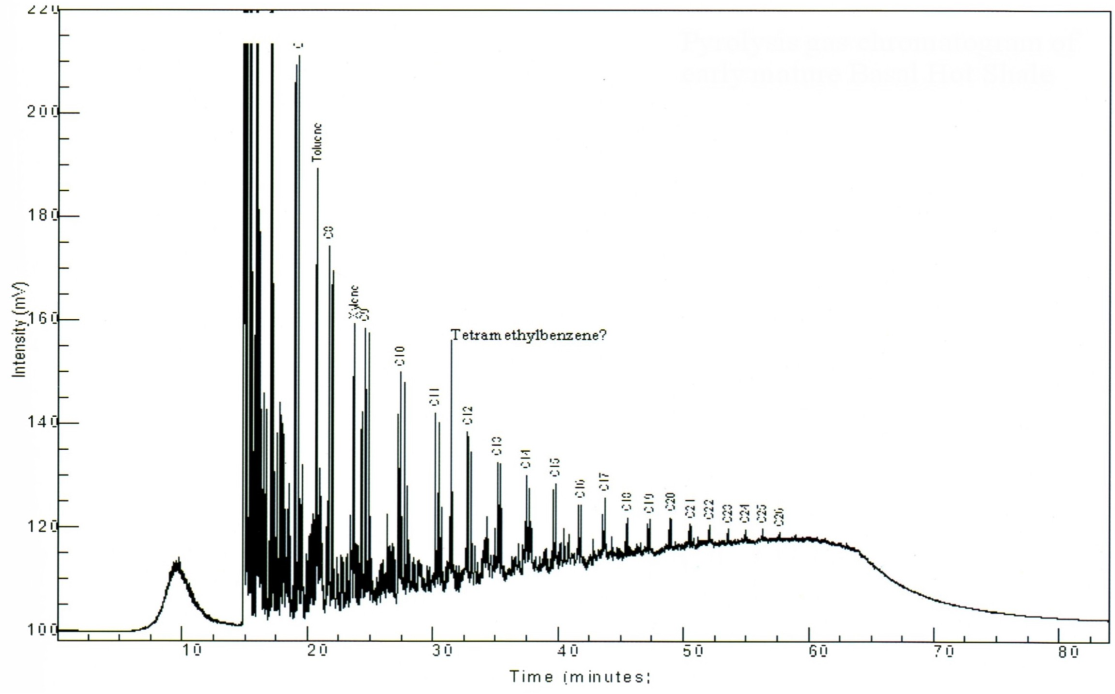


Figure 78.- Pyrolisis gas chromatogram of an early mature Hot Shale sample. From Hall et al.

(Ro<0.5%) and only one (the deepest) falls into the late mature field (Ro>1.4%).

Seven kerogen samples from seven wells distributed across the Murzuq Basin were isolated and analysed by counting 200 particles in order to characterize the main kerogen components: Amorphous organic matter, phytoclasts and palynomorphs (Ismail et al, 2002). Results are plotted in figure 77. Amorphous organic matter (AOM) is the main kerogen component; it constitutes over 80% in six of the seven analysed samples, giving a type II kerogen assemblage. The sample of well P1-NC101 is the exception to this, with an AOM content of 40% (Pa = 36.5% and Ph = 23.5%), giving a type II/III kerogen assemblage. In general, the phytoclast content is greater than the palynomorph content, apart from the samples from wells D1-NC151 and P1-NC101, in which palynomorphs slightly exceed phytoclasts. The high AOM content of these samples suggests they were deposited in a distal environment removed from active sources of terrestrial organic matter, although the age of the studied samples (Early Silurian) could also explain the low phytoclast content.

Kerogen composition has been also evaluated using pyrolisis gas chromatography. The pyrolisate composition of Hot Shale samples (Fig. 78) has a low range of alkene/n-alkane doublets and a large UCM, suggesting predominance of algal and microbial origin for the organic components of this kerogen (Hall et al, 2012).

Bulk oil composition and physical properties have been analysed by Ismail et al. (2002) for eight samples derived from seven wells covering a wide zone of the northern and central Murzuq Basin. From north to south there are concession NC186 (wells A1 and B1); concession NC115 (wells A10, B10 and H10); concession NC174 (well F3) and the southern concession NC101, in the

well	oil composition							physical properties				
	C (wt%)	H (wt%)	N (wt%)	S (wt%)	Ni (ppm)	V (ppm)	Wax (wt%)	API	Pour Point (ºC)	Kinematic viscosity (cst)		
										25 ºC	40 ºC	60 ºC
A1-NC186	86.29	13.16	0.24	0.31	2	1	1.9	39.5	< -30	2.8	2.4	1.9
B1-NC186	86.16	13.41	0.09	0.34	2	2	1.4	39.0	< -30	3.4	2.7	2.3
E2-NC101	86.01	13.55	0.10	0.34	2	<1	6.4	31.8	6	16.9	9.7	6.4
E2-NC101	85.72	13.73	0.14	0.41	1	<1	6.0	36.5	15	7.0	4.7	3.4
F3-NC174	85.77	13.56	0.35	0.31	11	13	1.9	36.1	< -30	4.8	3.6	2.7
A10-NC115	85.66	13.47	0.17	0.70	1	<1	2.6	40.9	< -30	2.9	2.4	2.2
B10-NC115	86.06	13.49	0.06	0.39	1	<1	2.1	39.9	< -30	3.0	2.4	1.8
H10-NC115	85.85	13.33	0.27	0.55	<1	<1	1.3	40.3	< -30	3.0	2.2	1.9

Table 3.- Bulk oil composition and physical properties for selected crude samples. From Ismail et al. (2002).

central Murzuq Basin (well E2, two samples). Results are shown in Table 3.

In general carbon content is high, ranging between 85.66% and 86.29% in weight, and sulphur content is low, 0.31% to 0.70% in weight. Pour Point is very low, usually lower than -30ºC except for the two samples of well E2-NC101, in the central basin, which reach up to 6 and 15ºC respectively, accordingly these two samples have the higher wax content.

Crude samples have low density, with API degrees ranging between 31.8 and 40.9. The heaviest oils belong to the southern well E2-NC101; the rest of oil samples could be classified as light oils.

5. RESERVOIRS

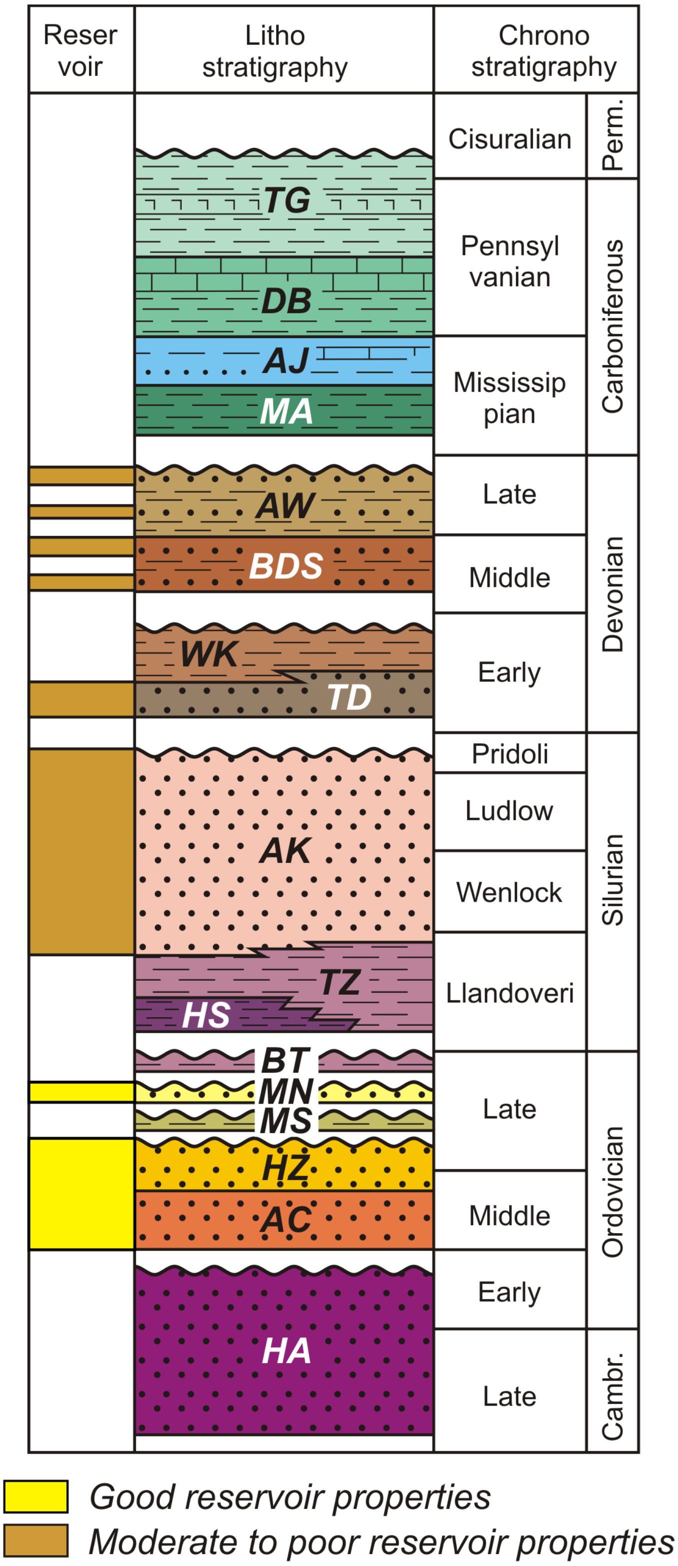


Figure 79.- Lithostratigraphic column of the sedimentary infill of the Murzuq Basin showing the potential reservoir units considered in this work.

The Palaeozoic sequence of the Murzuq Basin constitutes, together with the Palaeozoic sequences of most of North African basins in Algeria, Tunisia, Libya and Egypt one of the world's great concentrations of Lower Palaeozoic reservoirs (Crossley and McDougall, 1998), and despite the relatively poor exploration development in the Murzuq Basin, the main and prolific producing formations in the basin are the Palaeozoic units. According to Ismail et al (2002) the subsurface of the Murzuq Basin has many potential reservoir formations, the most of them in the Palaeozoic section, which includes (Figure 79) the Cambrian Hasawnah Fm, the Ordovician Hawaz and Mamuniyat Fms, the Silurian Akakus Fm and the Devonian Tadrart and Awaynat Wanin Formations (including their basal BDS Member), which locally display moderate to good reservoir properties and have oil shows and bitumen nodules, have not been proven to date as effective reservoirs and their contribution to discoveries in the Murzuq Basin is nil. To date, the successful discoveries in the Murzuq oil fields belong to the Ordovician Hawaz and Mamuniyat sandy units.

The Cambrian Hasawnah Formation has been studied by Aziz (2000) in seven wells from block

NC115, were the pebbly medium- to coarse-grained sandstones of their lower part contains abundant clay and quartz overgrowth diagenetic components reducing the pore space. This author considered that Hasawnah Formation has poor reservoir quality, although locally (an 30 ft thick interval in well A28-NC115) the formation reach up to moderate reservoir quality, with porosity ranging between 11.0 and 13.5% and permeability from 2 to few hundred mD, with a maximum value measured of 750 mD. These reservoir properties could be enhanced by fracture porosity, which has been reported from few cores.

The middle to late Silurian Akakus Formation has poor to very poor reservoir quality in the Murzuq Basin (Aziz, 2000), although it constitutes a good reservoir northwards, in the neighbouring Ghadamis Basin, were according to data from Tandircioglu et al. (2002) it has porosity values ranging from 7.6 to 29.5 % (average 19.9%) and permeability from 0.31 to 1615 mD (average 239 mD). The porosity-permeability plot (Fig. 80) shows that there is not a clear relationship between the porosity and permeability for the Akakus sandstones.

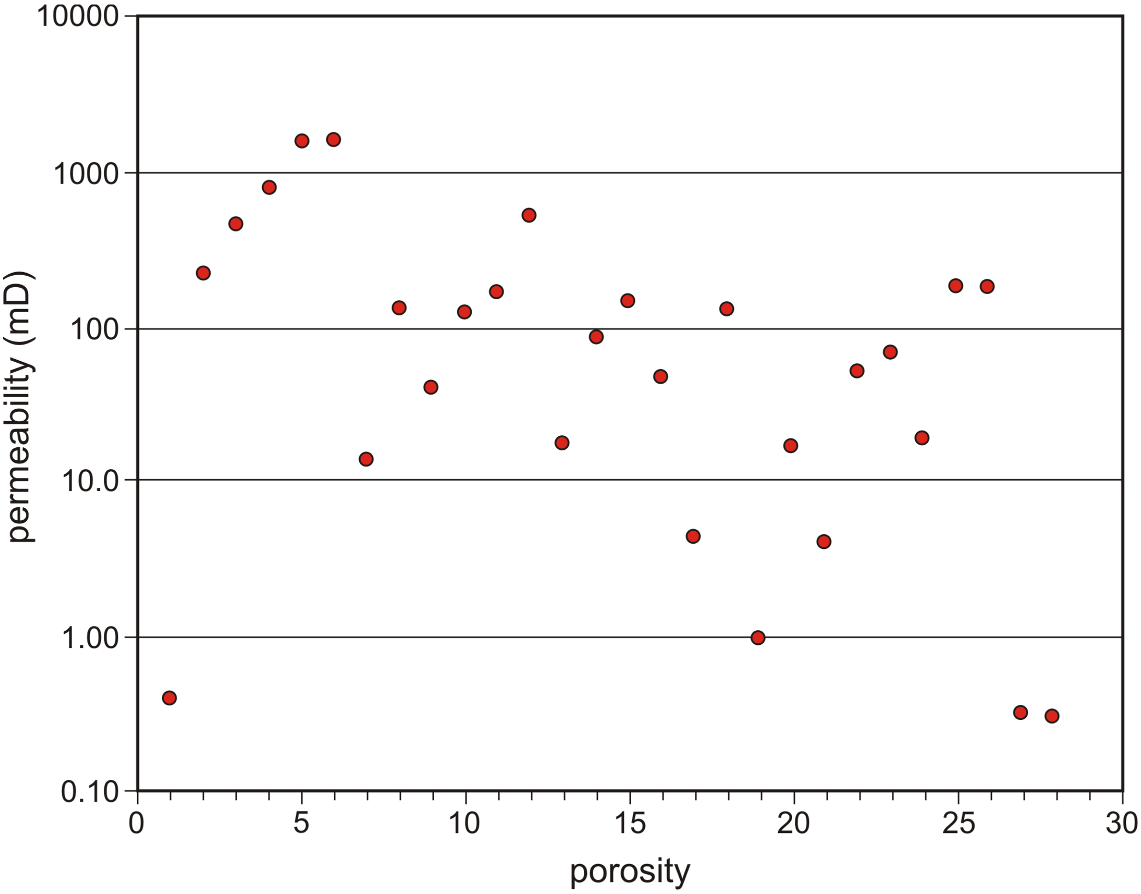


Figure 80.- Porosity vs permeability plot for the middle to late Silurian Akakus Formation. Data supplied from 28 core analysis from the subsurface of the Ghadamis Basin. From Tandircioglu et al. (2002).

In the Murzuq Basin the early Devonian Wan Kasa Formation has poor reservoir quality. However northwards, in the subsurface of the Ghadamis Basin where it has been drilled by a great number of boreholes the friable Wan Kasa sandstones constitutes a good oil reservoir (Aliev et al, 1971; Massa and Moreau-Benoit, 1976; Belhaj, 1996; Echikh, 1998), reaching up to 365 m in thickness in well E1-8 (Belhaj, 1996).

The middle to late Devonian Awainat Wanin Formation is considered to have a generally poor to very poor reservoir quality (Aziz, 2000) except in their basal part, where the BDS sandstones in considered by this author as a probable third target in block NC115. Although generally the BDS displays poor reservoir properties, locally it may reach fair reservoir quality. This is in disagreement with López (2010), which conclude that the BDS in block NC115 cannot be considered as a reservoir unit. It must be highlighted that in the Murzuq subsurface, the Awainat Wanin Formation displays major heterogeneity with regard to facies distribution and reservoir quality except in some areas close to the Tihembokah and Al Hamra highs (Echikh, 1998).

The fact that the Ordovician siliciclastic formations act as the main reservoir units in the Murzuq Basin is the result of their stratigraphic position. Really, the Ordovician Hawaz and Mamuniyat sandy formations are affected by erosive surfaces forming paleoreliefs, which provide lateral contact with the silty Tanezzuft Formation and the major source rock: their basal Hot Shale Member. In turn, the thick and widely extended Tanezzuft sequence acts as the main basin-scale top seal (see chapter 6), making difficult hydrocarbon migration from the basal Hot Shale to the overlying siliciclastic units. When Hawaz and Mamuniyat formations are present, both could act as reservoir units of a unique play but in some areas (e.g. blocks NC186 and NC 115, Franco et al, 2012) where lateral seal is provided by the intervening Melaz Suqran Fm, usually they constitutes two separated reservoirs for two different plays.

In their study of the subsurface of block NC115 Aziz (2000) considered the Mamuniyat sandstones the main reservoir rocks in this block, whereas sandstones of the Hawaz Formation are considered as the secondary target. This author reported that Hawaz sandstones become more important when Mamuniyat section thins or it is absent.

5.1. HAWAZ FM RESERVOIR

The fine- to medium-grained sandstones of the Hawaz Formation represent the secondary reservoir target in the Murzuq Basin (Aziz, 2000), although in places where the Hawaz Formation directly underlies the Tanezzuft shales – as in the central Murzuq – the Hawaz sandstone constitutes the major oil reservoir (Aziz, 2000; Rodrigues et al, 2008). Hawaz Formation widely extents across the Murzuk subsurface with a depocenter in the central part of the basin (Fig. 30) and has been drilled by most of the Murzuq wells. As the top of the Formation is a deeply incised erosive surface, the Hawaz Formation thickness is very variable. This erosive surface is related to the late Ordovician glaciation, resulting in a complex palaeorelief forming a series of paleovalleys deeply carved by ice streams and the intervening paleohighs ("buried hills" in the literature).

Petrography and petrophysics of the Hawaz Sandstones:

In general, the Hawaz sandstones show slight grain size variations. They mainly consists of very-fine to fine-grained quartzarenite, although occasionally medium- and coarse-grained sandstones have been reported. Their grains are rounded to subrounded and moderately to well-sorted. Ramos et al (2004) in a study based in 154 samples from the Gargaf outcrops found an average composition of $Q_{99}F_1L_0$, whereas Abouessa and Morad (2009) in a work based on 102 samples from outcrop (Gargaf) and subsurface (well A28) found a sandstone composition averaging Q_{95} F_4 L_1.Quartz grains are mainly monocrystalline and subordinate coarse-polycrystalline; rarely polycrystalline. The second detrital component is feldspar which is dominated by microcline with trace amounts of plagioclase. Mica (muscovite and subordinate amounts of biotite), rock fragments and intraclasts also occur in small amounts. Heavy minerals are present as scattered grains of zircon, garnet, tourmaline and rutile. According to Abouessa and Morad (2009) the subsurface sandstones have slightly higher quartz and lower feldspar content than the outcrop sandstones, whereas the amount of mica do not vary between the subsurface and outcrop sandstones.

Diagenesis has a complex impact on the evolution of reservoir quality in sandstones. According to Abouessa and Morad (2009) diagenetic evolution of the Hawaz sandstones include eo- meso- and telodiagenetic processes. Subsurface samples only are affected by eo- and mesodiagenetic alterations, whereas outcrop sandstones have also undergone telodiagenesis.

During eodiagenesis, which occurs at near surface and shallow burial conditions, the main diagenetic modifications to the Hawaz sandstones were kaolinite and pyrite formation and mechanical compaction. Kaolin appears as scattered patches composed of booklet- and vermiculate-like stacked crystals, which have resulted from replacement of the feldspars and mica grains (Abouessa and Morad, 2009; Abouessa, 2012). Kaolin occurs in similar amounts in subsurface and in outcropping sandstones, but it is most frequent in the coarse (medium-grained) sandstones.

At deep burial conditions mesodiagenesis processes took place; during this diagenetical phase quartz overgrowth, illite formation and chemical compaction were the main diagenetical processes. Quartz cement is the main diagenetic mineral occurring in similar amounts in outcrop and subsurface sandstones, but it is most abundant in the coarser (medium-grained) sandstones. Quartz cement occurs as syntaxial overgrowths which cover the detrital quartz grains, and as prismatic crystals (outgrowths). Illite, which is the second-most common clay mineral in the Hawaz Formation sandstones, occurs in small amounts; it is most abundant in the subsurface sandstones. Illite exhibits textural forms indicating a diagenetic origin, probably formed by replacement of mica and feldspar grains. It also occurs as pore-bridging fibrous and filamentous crystals.

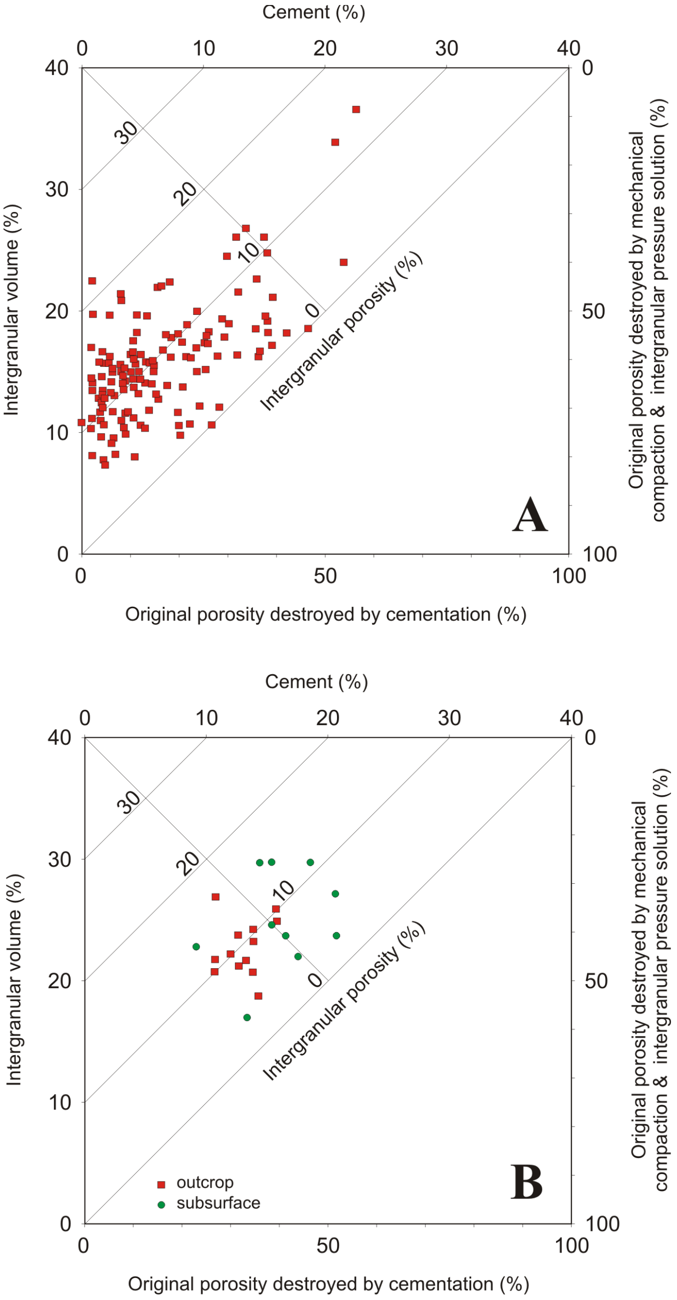


Figure 81.- Houseknecht diagrams showing the loss of original porosity by cementation, phisical or chemical compaction for two Hawaz sample sets. **(A)** According to Ramos et al (2004). **(B)** According to Abouessa and Morad (2009).

During telodiagenetical evolution, which occurs during uplift and exhumation conditions, calcite and goethite precipitation were produced. For this reason both minerals only are present in the outcrop samples. Calcite occurs mainly as microcrystalline aggregates replacing quartz, feldspar and mica being in some cases closely associated with kaolinite.

The compaction degree of the Hawaz sandstones was evaluated by Ramos et al. (2004) and Abouessa and Morad (2009) by counting grain contacts in thin section; point counting has also been performed by these authors to calculate the porosity and cement percentages in order to evaluate the degree of chemical and mechanical compaction as well as the porosity reduction by cementation. In order to discriminate which of these diagenetical processes, chemical or mechanical compaction and cementation, have had most influence in the porosity loss, the data have been plotted in a Houseknecht diagram (Fig. 81). This indicates that the Hawaz sandstones have reduced their initial intergranular porosity between 9 to 42%, mainly by mechanical compaction.

Porosity of the Hawaz sandstones has been measured by thin-section (Ramos et al, 2004; Abouessa and Morad, 2009 and Abouessa, 2012), Helium (Abouessa and Morad, 2009 and Abouessa, 2012) and mercury intrusion (Ramos et al, 2004). Davidson et al. (2000) also reported porosity data of 77 samples from wells of block NC174, but these authors don’t indicate the measurement procedure.

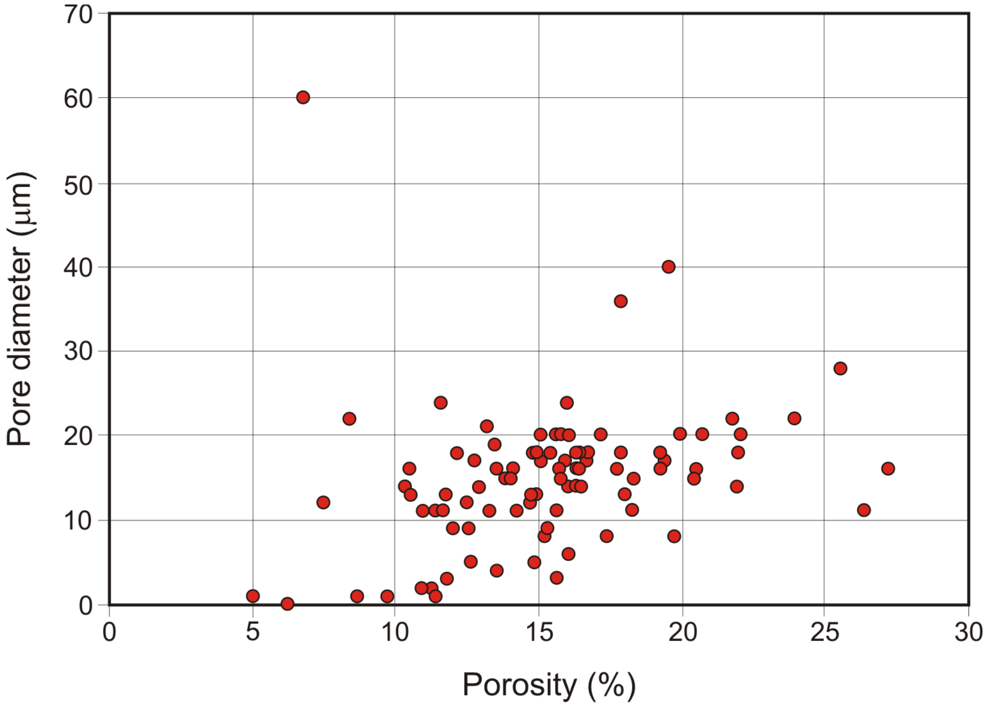


Figure 82.- Porosity vs pore diameter cross plot for the Hawaz sandstones. From Ramos et al. (2004).

Thin-section porosity of the Hawaz sandstones reaches from 1.0 to 22.6% (average 9.4%) in the 154 outcrop samples studied by Ramos et al (2004), and 3 to 20% (average 11%) in the outcrop and subsurface samples analysed by Abouessa and Morad (2009). It includes primary intergranular and secondary intragranular. mouldic and microfracture porosity. Micro-porosity (< 5 μm) is common between kaolin and illite crystals and within partially dissolved feldspar grains. Pore conectivity appears to be good, mainly in sandstones with total porosity greater than 8%.

In the core plug samples analysed by Abouessa and Morad (2009) porosity ranges between 0.2 and 21% (average 9.5%), whereas the samples measured by Ramos et al. (2004) by mercury intrusion porosimeter, porosity range between 5.0 and 27.5% (average 15.7%) with pore diameter ranging from 0.1 μm to 64 μm (average 14.6 μm). Assuming that the initial porosity loss is the result of compaction and cementation processes, Ramos et al (2004) propose a plot showing the narrow relationship between the total porosity and the pore size (Fig. 82).

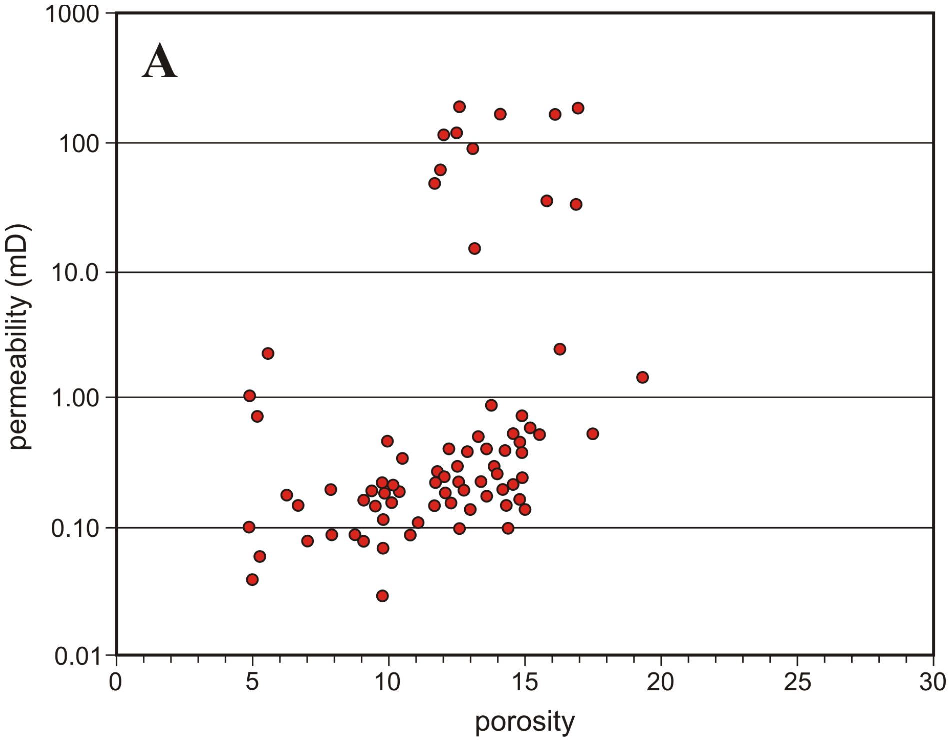
In their subsurface study of block NC115, Aziz (2000) reported porosity data of the Hawaz Formation. According to this author, the reservoir quality of the formation varies from poor to good. Within the H field the upper parts display high shale content with sandstone porosity ranging from 6 to 12%, while the lower part has better quality and form the main reservoir zone, with porosity from 10 to 16%. In the C and F structures, where quartz overgrowth and recrystallized illite are abundant, the formation reaches their poorest quality within the block. Porosity in F1-NC115 and F2-NC115 ranges from 3.6 to 14.6 %. In contrast, the E and L structures show better reservoir quality, with measured Hawaz porosities of 15.0 to 19.0%.

Davidson et al. (2000) reported porosity data from a set of 77 samples of the subsurface of block NC174. According to these authors the Hawaz sandstones have porosity values ranging from 4.8 to 19.2%, with an average of 11.8%.

A REMSA internal report supplied porosity data for the Hawaz interval in well J1-NC186 ranging from 9.0 to 16.0%, with an average of 13%. The same report point out good reservoir quality, with porosity > 20% in well D1-NC190.

Permeability data are reported by Davidson et al (2000), Aziz (2000), Ramos et al. (2004) and Abouessa and Morad (2009).

The permeability data supplied by Davidson et al (2000) are about the same porosity tested 77 core samples of the subsurface of block NC174 above mentioned. According to these authors permeability ranges between 0.03 and 190 mD, with an average of 16.4 mD.



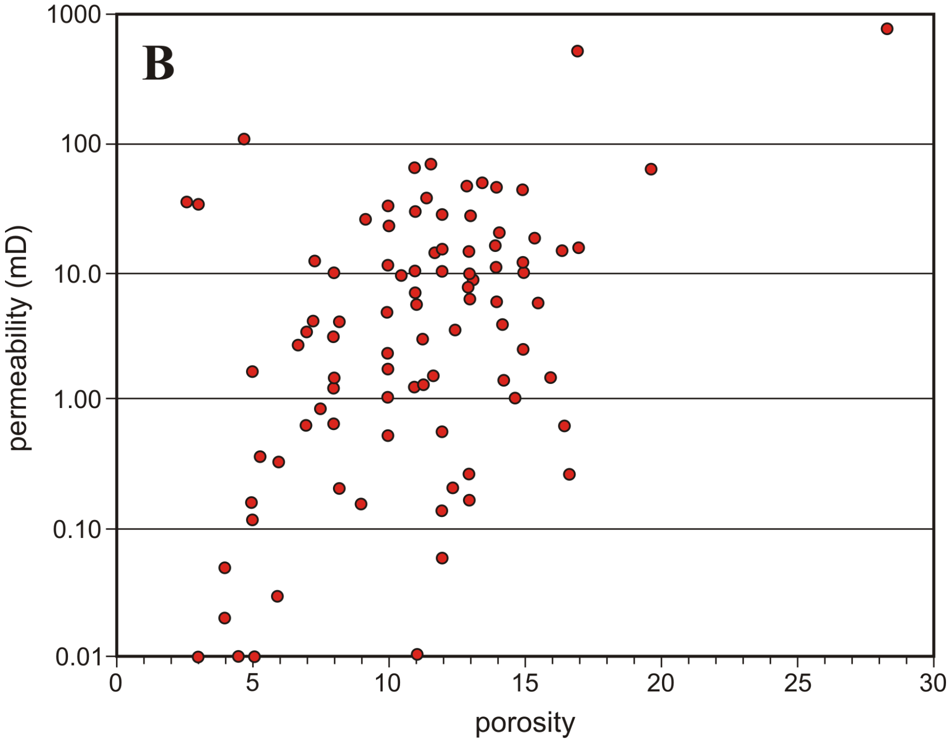


Figure 83.- Porosity vs permeability plot for the Hawaz sandstones. **(A)** After Davidson et al. (2000). **(B)** After Ramos et al. (2004).

In their work on the subsurface of block NC115, Aziz (2000) detect important variations in the Hawaz sandstones. The upper part of the formation has low permeability values within the H field, with measured values ranging between 0.2 and 2.5 mD, although the lower part, which constitutes the main reservoir zone, has better quality and permeability values from 6 to 900 mD has been measured. As in the porosity distribution, the poorest reservoir quality within the NC115 block is found in the C and F fields, where permeability generally range from 0.02 to 0.32 mD, although locally (F1-NC115) a maximum of permeability of about 50 mD has been measured.

Ramos et al. (2004) supplied permeability data of 92 samples derived from the Hawaz outcrops in the Gargaf; according to these authors, the permeability of the Hawaz sandstones range between 0.003 and 800 mD, averaging 30.5 mD, of these 92 tested samples, 40 of them supplied horizontal permeability data, with values between 0.003 and 800 mD (average 42.8 mD) and the remaining 52 samples are non-horizontal (vertical or oblique), resulting permeability values ranging from 0.07 and 536 mD (average 21 mD).

Abouessa and Morad (2009) don’t report directly permeability data, but supplied a series of plots relating vertical and horizontal permeability with other parameters as depth, and porosity. The represented values of vertical porosity range between ca 0.002 to 1000 mD, whereas the horizontal porosity varies between 0.003 and 900 mD.

The above mentioned REMSA report of well J1-NC186 reported permeability values ranging between 0.09 and 0.16 mD, with average of 0.13 mD.

In general, the Hawaz sandstones show a relatively weak correlation between porosity and permeability (Fig. 83).

5.2. MAMUNIYAT FM RESERVOIR

According to Aziz (2000) the coarse-grained siliciclastic Mamuniyat Formation represents the primary reservoir target in the Murzuq Basin. The formation has been penetrated by the most of the wells drilled in the basin because it has a widespread distribution (Fig. 38). The limits of the Formation are easily identifiable by logs, with the base defined by the shales of the Melaz Suqran Formation and the top defined by the shales of the Bir Tlacsin or Tanezzuft formations. In the subsurface the thickness of the Mamuniyat Formation is highly variable, from few hundreds of meters to absent. Sedimentary architecture of the Mamuniyat Formation is complex, it displays internal erosive surfaces and complex vertical and lateral facies variations as well as major heterogeneity (Le Heron et al, 2006).

Petrography and petrophysics of the Mamuniyat Sandstones:

In the Murzuq subsurface Mamuniyat Formation broadly constitutes a coarsening-upwards detrital sequence made up by grey coloured fine- to coarse-grained even conglomeratic sandstones displaying different shorting. Major detrital components are quartz (80 to 97%), lithic fragments (2 to 4%) and micaceous grains (2 to 3%). Silica cement with different textures is common and sometimes a mixed silica-kaolinitic cement is also present. According to Davidson et al. (2000), the reservoir quality of the Mamuniyat sandstone depends on a combination of primary compositional and textural factors combined with secondary compactional and diagenetic factors. Mamuniyat reservoir quality tends to increase with increasing grain size and sorting, and decreasing detrital clay content. These primary factors can be strongly overprinted by secondary factors, which tend to reduce the reservoir quality of the sandstone through compaction and precipitation of authigenic cement and clay minerals. One exception to this reduction in reservoir quality is that of feldspar dissolution, which can increase the porosity and permeability.The main porosity type of the Mamuniyat sandstones is the primary interparticle porosity; although in some areas (i.e. block NC115, Aziz, 2000) image logs reported the presence of fracture and microfracture secondary porosity enhancing the porosity of the Formation.

The Mamuniyat Formation fills a palaeorelief originated by the previous late Ordovician glaciation and consequently it typically displays major thickness variations (see section 3.2.5). In turn, reservoir quality of the Mamuniyat sandstones displays major rapid facies variations and heterogeneities (Le Heron et al, 2006) and internal erosive surfaces (Deinoux et al, 2000; McDougall et al, 2005), resulting in a very complex sedimentary architecture. In the subsurface of block NC115 Aziz (2000) reported good reservoir quality of the formation in the, although with major variation within the same field. The sand/shale ratio in the Mamuniyat Formation is generally high, averaging 0.8, and when this ratio is high it is possible that good permeability might be present (Davidson et al, 2000).

In spite of the highly variations of the petrophysical properties of the Mamuniyat Formation, figure 84 show the broad trend of the distribution of the porosity for the upper Mamuniyat Formation in the Murzuq subsurface. The lowermost porosity zone is located in the central Murzuq, were it is lower than 5%. The main porosity gradient is towards the west, reaching porosities values >20 – 25% southwards Ghat. Towards the north, south and east the trend of the

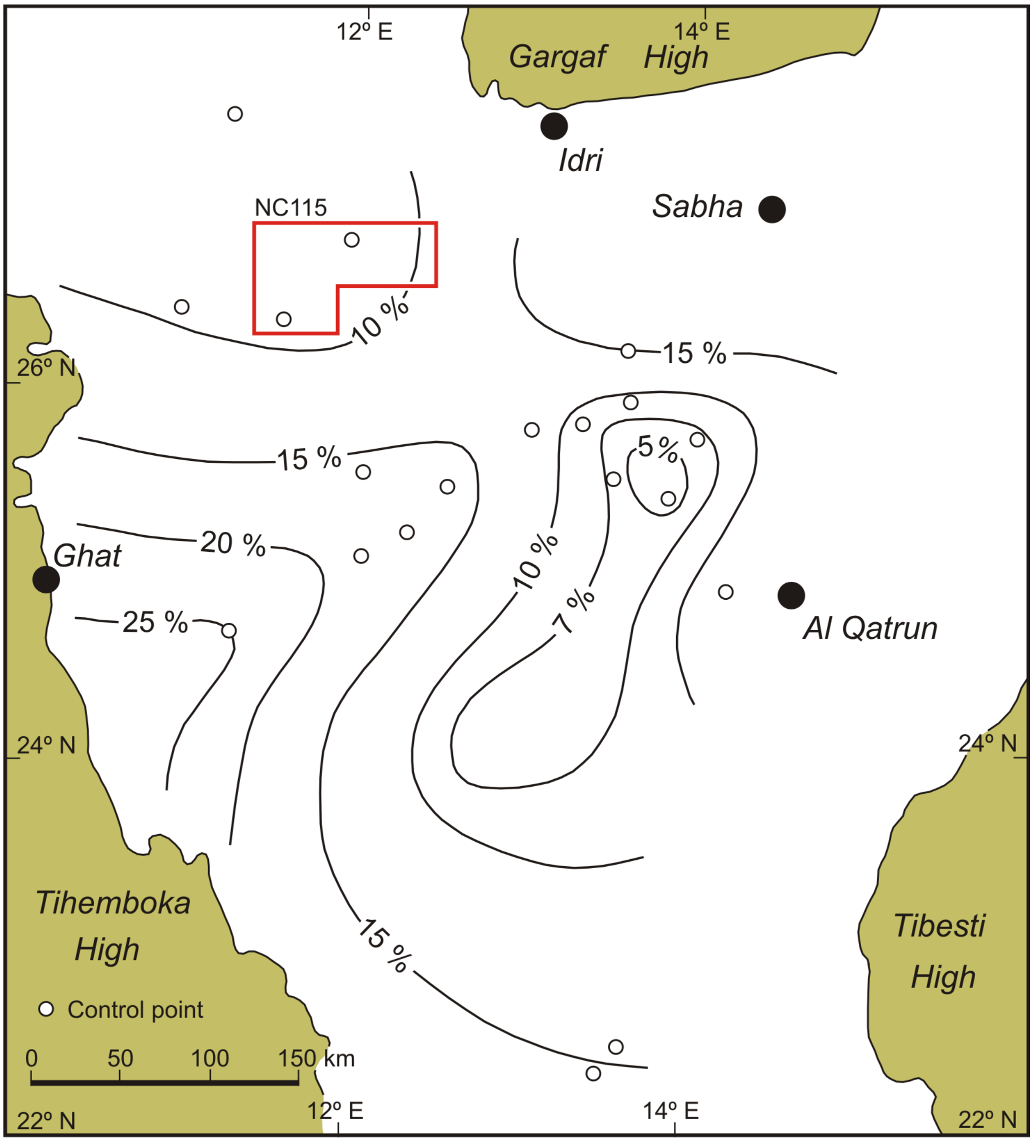


Figure 84.- Upper Mamuniyat porosity distribution across the subsurface of the Murzuq Basin. Red inbox indicates the location of NC115 block and data supplied by Aziz (2000).

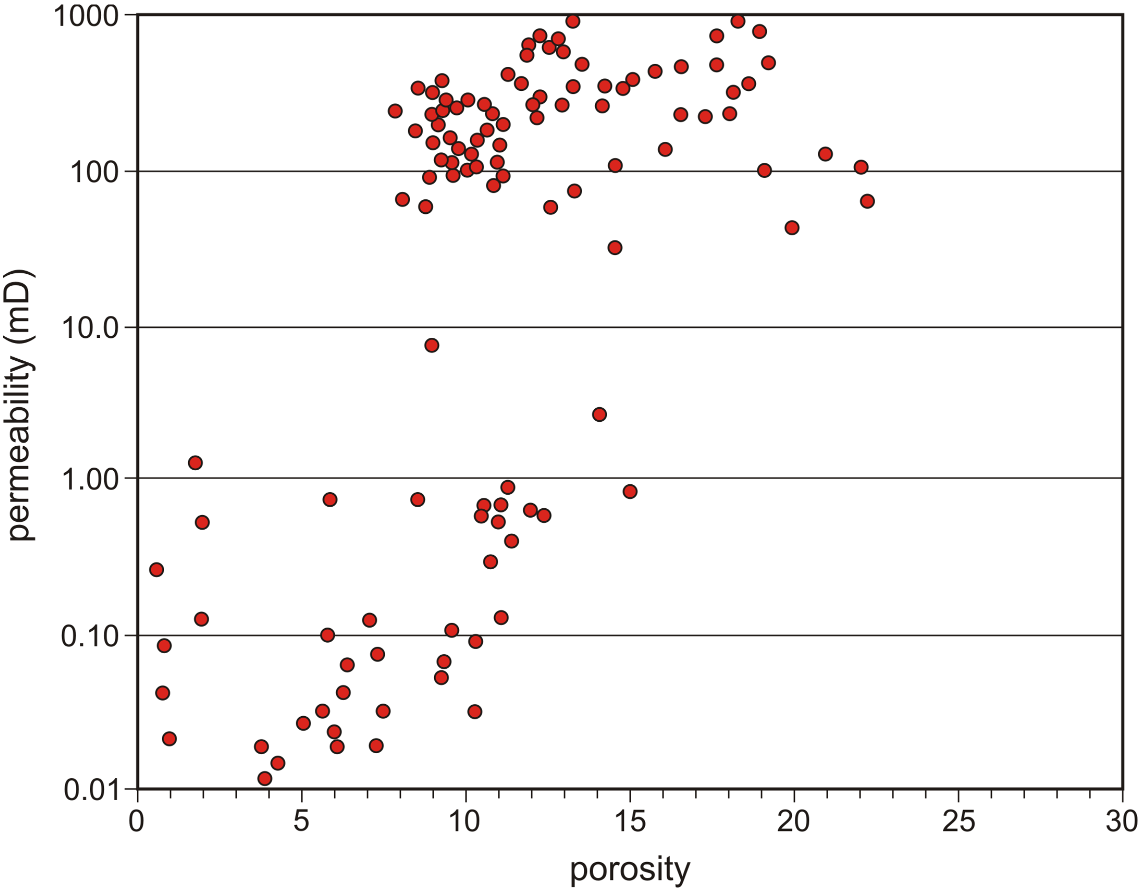


Figure 85.- Porosity vs permeability plot for the Mamuniyat sandstones. Modified from Davidson et al. (2000).

porosity increase is lower. It must be highlighted that despite this general trend, the porosity values for a given zone displays great variability. For example, in the subsurface of block NC115 (red inbox in Fig. 84), Aziz (2000) reported poor reservoir quality in the northern part (well A2-NC115), with porosity values ranging between 5 and 12% and permeability between 7 and 160 mD. Reservoir quality slightly increases in the central and southern parts of the field, reaching porosity values from 9 to 16% and permeability values between 115 and 1850 mD in well A1-NC115. The better reservoir quality in NC115 block are reported from the H-field, which show fair to good quality, with average porosity of 13 to 15 % and permeability from 84 to 1017 mD in well H2-NC115. Aziz (2000) reported again much variation within the B-field, which have moderate to poor reservoir quality in their central and northern parts, with porosity values ranging from 9 to 12% and permeability from 1 to 11 mD (well B31-NC115), while the southern segments, where the periglacial unit is missing, show better quality, with porosity averaging from 9 to 13.5% and permeability ranging from 18 to 700 mD in well B3-NC115.

Davidson et al (2000) reported reservoir quality data from a set of 114 samples of Mamuniyat sandstone from the subsurface of block NC174. According to these authors, porosity values range from 0.5 to 23 %, averaging 10.9%, whereas permeability ranges between 0.01 and 890 mD, with a mean of 175 mD. The porosity vs permeability cross plot (Fig. 85) shows as there is no a simple overall relationship between the porosity and permeability of the Mamuniyat sandstones in the NC174 wells, although a relationship exist in individual wells. The lack of a unique poro-perm trend is related by Davidson et al (2000) to primary facies variations as well as differences in the secondary diagenetical processes. Figure 85 also shows as two point clouds exists; one of them belonging to samples with good to moderate reservoir quality, with porosities ranging from 8 to 23% and permeabilities of 90 to 1000 mD. The other one shows significantly poorer reservoir quality, with low to moderate porosity ranging from 1 to 11% and low permeability (less than 1mD). The relatively low porosities, even in the clean sandstones, mainly result from the abundance of quartz overgrowths and subordinate siderite, dolomite cements and the presence of illite.

6. SEALS AND TRAPS

6.1. SEAL ROCKS:

As has been above exposed, the Palaeozoic sedimentary record of the Murzuq Basin contains a number of thick, laterally continuous shaly units able to sealing (Fig. 86). However, at a basin-scale only the shales of the marine Tanezzuft Formation have been reported as effective top seal, except in few localities where the Middle to Late Devonian shales of the Awainat Wanin Formation also contributed as top seal rock for secondary (Devonian) plays. Lateral seal is provided by the fine-grained low permeability rocks of the Ordovician Melaz Suqran and Bir Tlacsin Formations.

All the commercial finds in the Murzuq Basin have the thick Tanezzuft Formation as top seal. The sealing capacity of the Tanezufft shales is generally good, especially in areas where the lowermost Hot Shale Member – deposited in deep marine environments – is present, as in the northwestern parts of the basin. However locally, over some paleohighs as the A-NC115 structure or over the regional Traghan and Tiririne paleohighs, where the Hot Shale Member was never deposited, the Tanezzuft Formation becomes silty or sandy with a poorer sealing capacity. In general, the most silty composition of the Tanezzuft Formation – and therefore their better sealing capacity – correspond with the central and northern parts of the Murzuq Basin (Fig. 47) whereas towards the south and east the Tanezuft Formation becomes more sandy and therefore, their sealing capacity diminishes.

Due to erosional truncation during the Caledonian erosive phase the Tanezzuft shales are not presents across the whole of the Murzuq Basin, but the unit thins and are absent eastwards (Fig. 49). In areas where the Tanezzuft shale is absent or thin, the Mamuniyat or Hawaz reservoirs are capped by Devonian sequences with variable sealing capacities. In these areas, as over the western flank of Traghan High, the presence of numerous oil shows suggest that hydrocarbon migration may have occurred into the overlying Devonian strata, although the lack of commercial oil discoveries could be interpreted as the result of ineffective sealing capacity of the Devonian strata.

In some structures, as in the Hawaz “buried hills” (see next section) which have been widely reported by Craik et al. (2001) and Franco et al. (2012) in concessions NC115 and NC186 lateral seal is provided by the fine-grained Melaz Suqran and Bir Tlacsin formations filling the paleovalleys.

The degree of lateral continuity of the sealing surface, in addition to other factors such as lateral permeability and fault barriers, presents the principal control on the distribution of migration pathways.

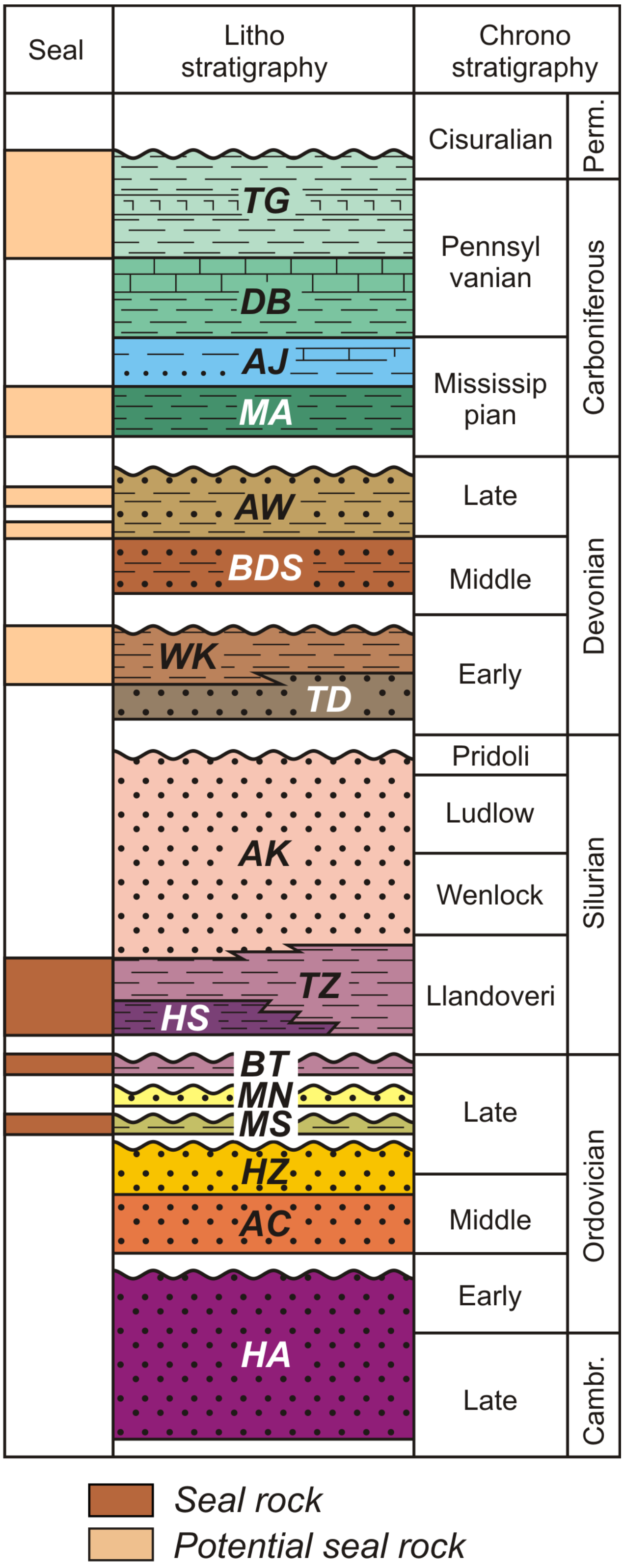


Figure 86.- Lithostratigraphic column of the sedimentary infill of the Murzuq Basin showing the potential seal units considered in this work.

6.2. TRAPS:

Up to four trap types have been described in the Ordovician reservoirs of the Murzuq Basin. From more frequent to more scarce they are: a) Hawaz “buried hills” b) lateral pinch-out of the Mamuniyat sandstones, c) single anticlines and antiform structures, and d) lateral closure by different fault types. The first two trap types are related to the palaeotopographic surface developed during the Upper Ordovician glaciation and the second two are structural traps.

a) Hawaz “buried hills”: Buried hills are geomorphological features that provide effective traps for the proven oil accumulations. This trap type is the most common in the Murzuq Basin, mainly in concessions NC115 and NC168 (Craik et al, 2001; Franco, 2012). Echikh and Sola, (2000) also reported this type of trap for the oil discoveries E1-101 and K1-101. It is constituted by erosional paleotopographic highs – called “buried hills” – (Fig. 16) which developed by direct erosional action of the ice sheet or subglacial meltwater during late Ordovician glaciation on the Middle Ordovician sequences, creating a topography of highs and lows; these highs are often made up by the Hawaz Formation, whereas the intervening paleovalleys are filled by the Mamuniyat Formation. Both, Hawaz and Mamuniyat sandstones are reservoirs and they are in vertical and lateral contact with Tanezzuft seal and Hot Shale source. Other units involved in the trap are the fine-grained Melaz Suqran and Bir Tlacksin formations, both with sealing properties. Figure 87 is a sketch not to scale of a

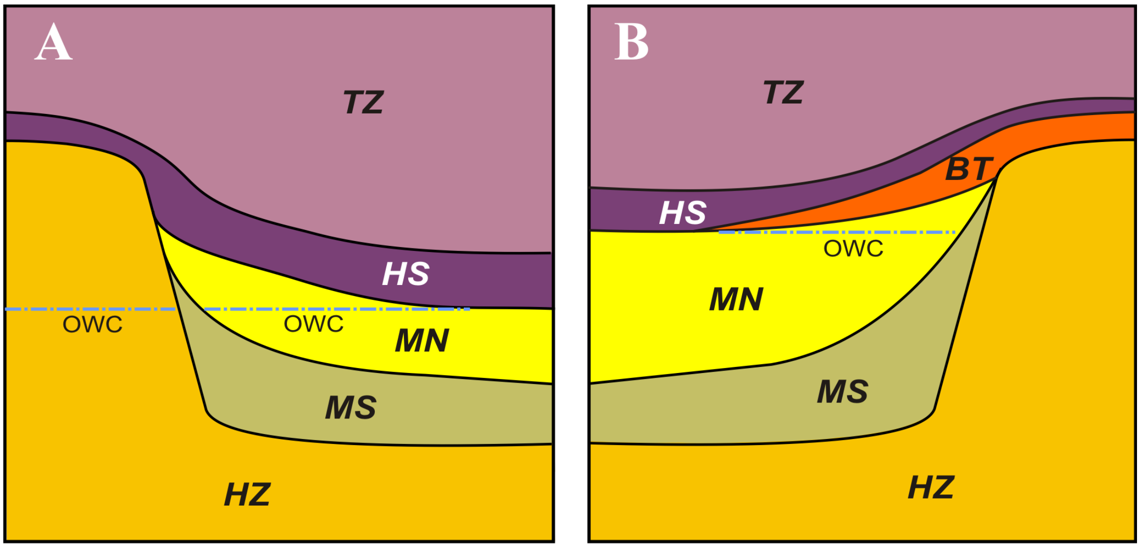


Figure 87.- Sketch not to scale of the typical trap configurations for the “buried hills” in the subsurface of the Murzuq Basin. See text for explanation. **HW** = Hawaz Fm. **MS** = Melaz Suqran Fm. **MN** = Mamuniyat Fm. **BT** = Bir Tlacsin Fm. **HS** = Hot Shale Mb. **TZ** = Tanezzuft Fm.

paleovalley between two paleohighs or “buried hills” showing some possible relation between the above mentioned units. The erosional surface was developed during the late Ordovician on the older sequences, normally over the Hawaz Fm. The following lithostratigraphic units Malaz Suqran, Mamuniyat and Bir Tlacsin formations preferably accumulated (but not only) filling the paleovalleys, which could result total or partially filled depending of their previous deep and the local sedimentary rate. Additionally, differential compaction and erosive relationships between these units could widely modify the resulting geometry. Melaz Suqran shales may acts as a lateral seal between Hawaz and Mamuniyat sandstones (Fig. 87.B) or not (Fig. 87.A). In the first case a pinch-out of the the Mamuniyat sandstones is produced. The patchy and discontinuous Bir Tlacsin shales may acts as top seal or lateral seal for both, the Mamuniyat or the Hawaz reservoirs (Fig. 87.B). When the Hot Shale Member are in direct contact with the Hawaz or Mamuniyat reservoirs (Fig. 87.A) and overlied by a thick Tanezzuft shale seal, one or two plays could developped.

The late Ordovician paleo hills are the oldest traps currently producing oil in Murzuq Basin. Franco et al (2012) documented this type of traps in concession NC186, where the play is defined at the base of the Tanezzuft horizon; in this trap the presence of the low density, low velocity Hot Shale creates a large impedance contrast over the reservoirs. Acording to Craik et al. (2001) seismic interpretation suggests all structures are filled to spill point.

b) Pinch-out of the Mamuniyat sandstones: The second trap mechanism would be a lateral pinch-out of the glaciogenic Mamuniyat Formation sands against Melaz Shuqran and/or Bir Tlacsin formations (Fig. 87.B) which locally would constitute a stratigraphic trap. Locally Mamuniyat pinch-out traps are enhanced by three- four-way Mamuniyt closures. Franco et al. (2012) also reported this type of trap from concession NC186.

c) Antiform structures: The Murzuq Basin has been submitted to a multiphase tectonic evolution and consequently shows a wide variety of structural traps types of different ages. The most prolific structural traps are single anticlines and antiforms of pre-Hercynian age. These folds are generally smooth, low-relief and small-sized structures (Fig. 88.A). According to Echikh and Sola (2000) this trap type is present in concessions NC58, NC101 and NC115. The discoveries within the Mamuniyat Formation in the Al Sharara A and B pools occur in simple, low amplitude, four ways dip closures (Craik et al, 2001). Some anticlines are affected by normal faults, originating normal faulted anticline traps which are also present in the same concessions in the Murzuq subsurface. One example of this trap type is the J1-NC115 oil discovery (Fig. 88.B).

d) Lateral closure by faults: Some reverse thrust-faulted anticlines form traps in NC115, as in the H and C fields, where the faults contribute to the seal on the eastern flanks of these fields (Fig. 88.C). The Elephant oil field is a

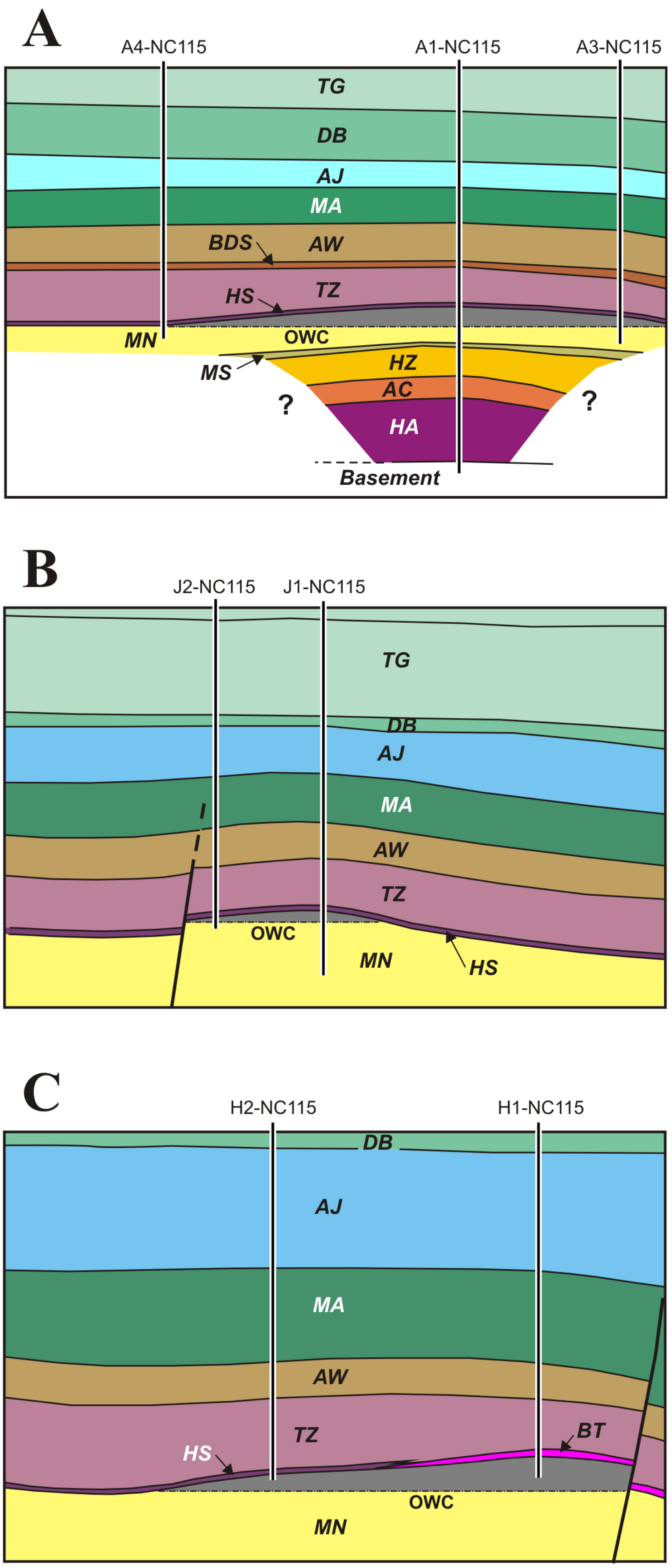


Figure 88.- Sketch not to scale of the different structural trap types documented in the Murzuq Basin. **HA** = Hasawnah Fm. **AC** = Achabiyat Fm. **HW** = Hawaz Fm. **MS** = Melaz Suqran Fm. **MN** = Mamuniyat Fm. **BT** = Bir Tlacsin Fm. **HS** = Hot Shale Mb. **TZ** = Tanezzuft Fm. **AW** = Awainat Wanin Fm. **MA** = Marar Fm. **AJ** = Assedjefar Fm. **DB** = Dembaba Fm. **TG** = Tiguentounine Fm.

combination trap comprising dip closure to the north, east and south and bounded to the west by a near vertical reverse fault. In general, the major, near vertical northerly and nortwesterly trending faults are in compression and provide effective seal even where they cut to surface, for example Lasmo's giant Elephant oil field. However, the minor faults aligned with NE-SW to E-W direction are a major risk to effective seal and trap.

In general, oil discoveries in the Murzuq Basin seem to be related primarily to old structures formed in Palaeozoic time with continued or rejuvenated Mesozoic growth (Echikh and Sola, 2000). Appraisal wells in licences NC101 and NC115 reveal significant lateral diagenetic changes within the Mamuniyat sandstones, suggesting diagenetic traps as a possibble play-type also in the Murzuq basin, but although the Tiguentourine Field in the nearby Illizi Basin provides an excellent example of a diagenetic trap, with a lateral permeability seal provided by increased quartz cementation within the Cambrian sandstones, no diagenetic traps have been reported up to date from the Murzuq Basin.

6.3. MIGRATION PATHWAYS:

Migration pathways of oil and gas depend of several factors such as source to reservoir communication, the nature of the seal, lateral changes in reservoir quality and the effects of faulting.

Up to date, all the commercial discoveries in the Murzuq Basin seem to be sourced from the basal Tanezzuft Hot Shale Member, and all the known commercial oil accumulations are within the underlying porous sandstones of the middle-late Ordovician Hawaz and Mamuniyat formations. Although preferred routes for hydrocarbon migration are controlled by several factors, including the structural morphology of the seal, lateral changes in reservoir quality and fault distribution, an efficient charging was facilitated by the source/ reservoir relationship. The proximity of the early Silurian Hot Shale source and the underlying midd-late Ordovician Hawaz and Mamuniyat reservoirs seems to be essential for any successful hydrocarbon accumulation in the basin. The importance of direct contact between source and reservoir is enhanced by the dominant Hawaz and Mamuniyat lithofacies – generally a relatively tight clean fine-grained quartzitic sandstone – that is not inductive to long distance migration (Echikh and Sola, 2000). This system is the primary play in all the major oil discoveries in the northern part of the Murzuq Basin.

In some areas of the Murzuq subsurface where the shaly Bir Tlacsin Formation is present, this unit apparently acts as a barrier for source rock to reservoir communication, preventing direct contact between the early Silurian source rock and the underlying Hawaz and Mamuniyat reservoirs. The importance of the Bir Tlacsin Formation in this respect seems to be capital; there is a certain geographical relationship between the subsurface distribution of the Bir Tlacsin Formation and the location of dry wells contra oil discoveries. This correlation between the presence of the Bir Tlacsin and dry wells also seems valid in the Ghadames Basin where the Mamuniyat reservoir has never been found to be oil-bearing in areas where the Bir Tlacsin Formation is present.

The only exception in this respect is in the Murzuq Basin itself, in the H-field in concession NC115. The successful well H1-NC115 drilled over the crest of the structure shows the presence of a thin Bir Tlacsin interval. However, the second well on the H-field (H2-NC115) drilled downflank from H1 and found that the Bir Tlacsin Formation is missing there, allowing direct contact between the source rock and the reservoir. In this case, the Bir Tlacsin has a patchy distribution and does not act as a barrier as hydrocarbons have probably migrated from the flanks of the structure.

Timing of oil generation and migration:

There are not general agreement between the authors about the timing of generation and expulsion of the hydrocarbons from the Hot Shale Member. Most of this disagreement may be owing to significant differences in the role played by Hercynian uplift and subsequent denudation, Mesozoic burial and Tertiary Alpine deformation. Thermal history of the basin is also a key input for the basin modelling remaining uncertain and existing data are inconclusive. Future works must be addressed to constrain the parameters to be used for modelling. There are basin modelizations from Aziz (2000), Echikh and Sola (2000) Davidson et al. (2000), Craik et al. (2001) and Galushkin et al (2014).

Based on geochemical studies of wells from the NC115 concession and taking uplift and erosion values for the Hercynian and Alpine tectonic phases of about 3000 and 1000 m respectively, Aziz (2000) supplied a burial history

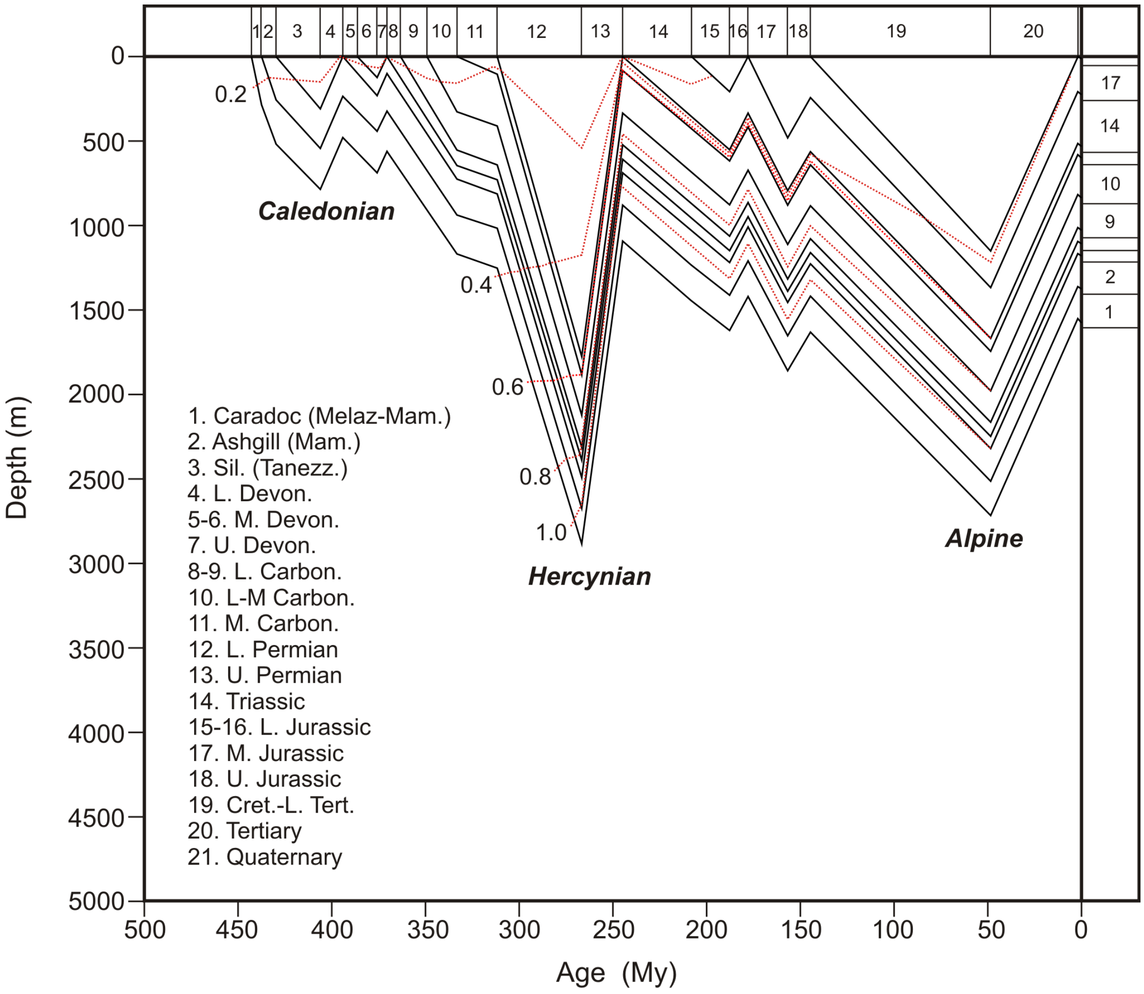


Figure 89.- Burial history diagram for maturity modelling of well H1-NC115. Redraw from Aziz (2000).

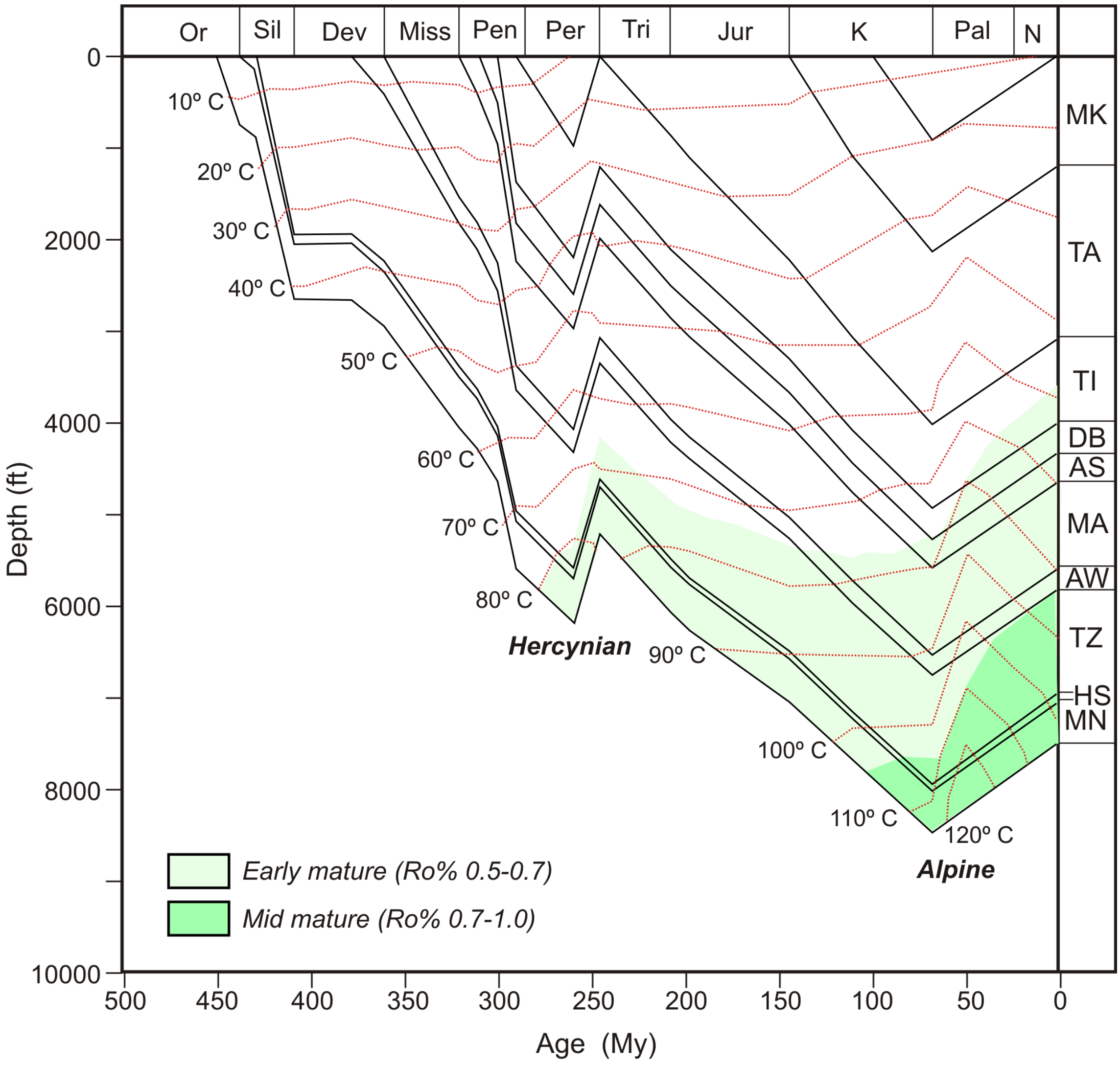


Figure 90.- Burial history diagram for maturity modelling of well B1-NC174. Redraw from Davidson et al. (2000).

diagram (Fig. 89) showing that the basal Tanezzuft Hot Shales entered the oil window during the Carboniferous to Permian. According to this author it is believed that the main oil generation taken place during the Carboniferous times, immediately prior to the Hercynian uplift.

Echikh and Sola (2000) suggest that the topographical lows containing the basal Tanezzuft Hot Shales became sites of significant subsidence during the carboniferous, although most of these lows could continue subsiding during the Mesozoic, and the Hot Shale source probably entered the oil-generating window during late Jurassic or early Cretaceous.

Davidson et al. (2000) supplied a maturity model based on wells data of the NC174 block (Fig. 90). They assume the present-day heat flow, but with the exception of a short early Tertiary period related to the Eocene volcanic activity occurred in the Murzuq borders, to which propose an increase of 20% in the heat-flow. These authors consider an uplift and erosion of about 300 m (1000 ft) for both, Hercynian and Alpine compresional phases. The results of their maturity model show that the Hot Shale source rocks might have entered in the oil window and start to generate significant quantities of oil about middle Cretaceous, and continued to do so until early Tertiary times.

A basin modelling has been carried out by Craik et al. (2001) in order to assess regional maturity and timing of generation and expulsion of hydrocarbons from the Hot Shale source rock. These authors have been calibrated the models with present-day temperatures and maturity data. The geological model assumed minor Hercynian erosion, maximum burial during Cretaceous times and significant Tertiary inversion of the basin during the Alpine cycle. Preliminarily their models suggest that in large areas of the basin, oil may have been generated from the Hot Shale Member during the Mesozoic times, from the Jurassic to the Cretaceous. Pre Hercynian oil generation, if present, is likely to have been restricted to the northwestern part of the basin.

Finally, Galushkin et al (2014) supply a burial and thermal history modelling for both, the Murzuq and Ghadamis basins. For the Murzuq Basin these authors suggest that the Hot Shale source rocks in the pseudo-well location began to generate hydrocarbons in the late Carboniferous, whereas the main phase of generation by these rocks in other parts of the Murzuq Basin occurred during the most recent phase of thermal activation during Cenozoic times.

In short, there are not agreement about the timing of oil generation in the Murzuq Basin, and depending of the different authors, which assume different inputs for their models, they find timing of oil generation from Carboniferous to Jurassic, Cretaceous or even Cenozoic times.

7. DISCUSSION

The Murzuq Basin contains a Palaeozoic sedimentary infill composed of up to fifteen lithostratigraphic units recording a time span from late Cambrian to Permian. Although this sedimentary record is relatively continuous, it is broken by a number of basin scale unconformities, the main of these are aged as late Ordovician, middle Devonian and late Carboniferous. The first one is related to the late Ordovician glaciation and caused a deeply incised palaeorelief which controlled the subsequent late Ordovician and early Silurian deposition. The middle Devonian and late Carboniferous unconformities are respectively related to the Caledonian and Hercynian tectonic phases and their following uplift and erosion. These two basin-scale erosive surfaces are responsible for the thinning and missing of a part of the pre-middle Devonian and pre-late Carboniferous sequences. The Palaeozoic lithostratigraphic units have been described in section 3 of this memoir and they are shown in figure 91. According to this description a number of units have good reservoir properties; two of them are good source rocks and few of they have good quality for sealing.

Palaeozoic Source Rocks:

According to the exposed in section 4, there are up to five lithostratigraphic units which, at least locally, have moderate to high TOC content and consequently they could be considered as potential source rocks; these units are (Fig. 91) the late Ordovician Melaz Suqran and Bir Tlacsin formations, the early Silurian Tanezzuft Fm and their basal Hot Shale Member, the middle to late Devonian Awainat Wanin Fm including the fine-grained intervals within the Basal Devonian Sandstones (BDS) and the early Carboniferous Marar Formation. However, it must be highlighted that all these units, except the early Silurian Hot Shales, have not been proven source rocks to date and their contribution to discoveries in the Murzuq Basin is speculative. Some of them have variable TOC contents, and most of them have not enough burial and are immature.

Only the early Silurian Hot Shale Member is considered as an oil-prone source rock for all the discoveries in the Murzuq Basin. However, deposition of the organic-rich shales filling topographical lows during early Silurian times resulted in an irregular distribution of the Hot Shales Member. This irregular distribution is boosted by the Caledonian unconformity, which thins or removes the Silurian sequences (see Fig. 10). Figure 92 shows as the subsurface Silurian Hot Shales are absent in the northern, eastern and western parts of the basin, whereas to the south the Hot Shale Member seems to be continuous, extending to the Djabo Basin in Niger. On the other hand, regional geochemical studies (Ismail et al, 2002; SOC, 2002; NRG, 2002; Martin and Barnad, 2003), reveal that the peripheral Hot Shales placed in the subsurface of the Murzuq Basin have not enough burial to reach the oil window, and consequently they remains immature to marginally mature (Fig. 92) and only the deeper buried Hot Shales of the central part are mature and could generate

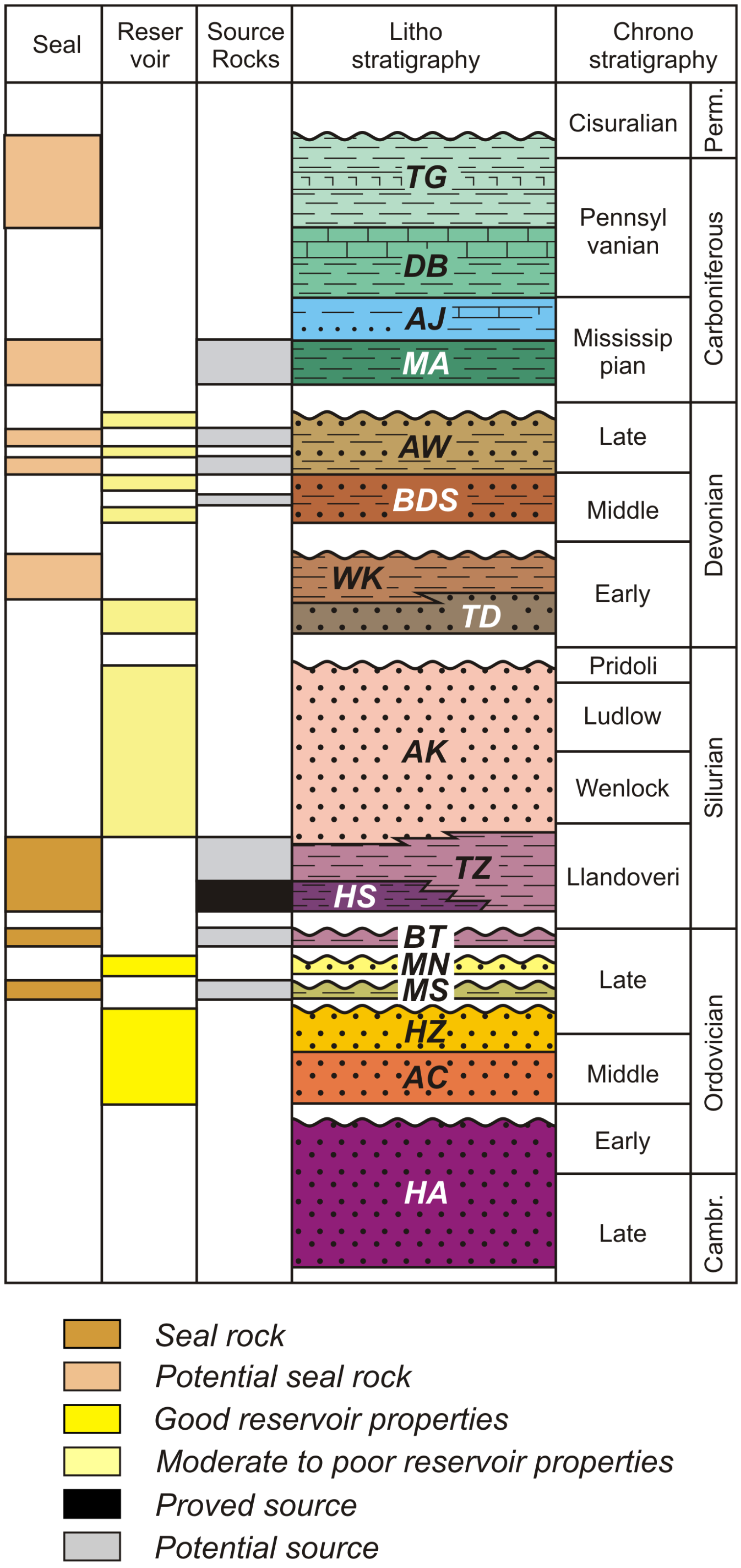


Figure 91.- Lithostratigraphic column of the sedimentary infill of the Murzuq Basin showing the potential source, reservoir and seal units considered in this work. This figure compiles the information supplied by figures 72, 79 and 86.

and expelled significant volumes of hydrocarbons.

As was described in section 3, the Tanezzuft Formation including their basal Hot Shale Member shows a rough regional facies change, becoming sandier towards the South and Southeast (see Fig. 47). This increase in the sand content results in a poorer source quality of the Hot Shale in these areas (Fig. 92).

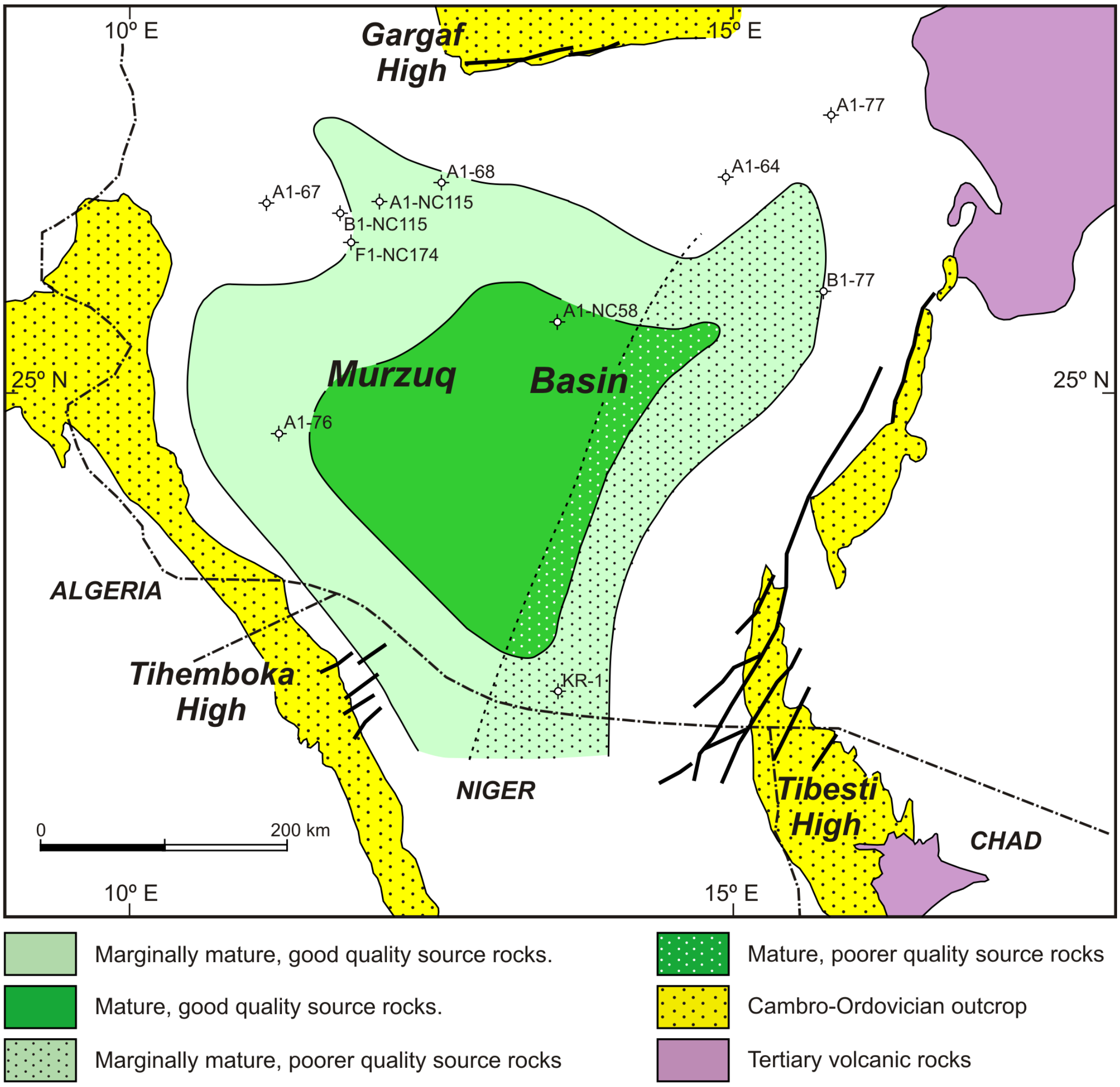


Figure 92.- Areal distribution across the Murzuq subsurface of the Hot Shales showing their maturity degree and source quality.

Palaeozoic reservoirs:

According to the above exposed in section 5, there are two main lithostratigraphic units displaying good reservoir properties: the middle to late Ordovician Hawaz and Mamuniyat formations (Fig. 91). Both are thick extensive detrital units which have been penetrated by most of the wells drilled in the basin. They are dominantly made up by quartzarenites with slight grain size variations, and although they have a complex sedimentary architecture with lateral facies variations, internal erosive surfaces and depositional and diagenetical permeability barriers, Hawaz and Mamuniyat formations are the primary targets in the Murzuq Basin with good porosity and permeability values. Generally the Hawaz and Mamuniyat sandstones show a relatively weak correlation between porosity and permeability, probably due to the presence of matrix.

Other potential reservoir units within the Palaeozoic sedimentary infill of the Murzuq Basin are (Fig. 91) the middle to late Silurian Akakus Formation, the early Devonian Tadrart Formation, the middle to late Devonian Awaynat Wanin Formation including their Basal Devonian Sandstone (BDS) Member and the early Carboniferous Marar Formation. However, it must be highlighted that all of these potential reservoir units have poor to fair reservoir properties and have a stratigraphic position hampering their connection with the source rock. Only the BDS have frequent oil shows and locally are considered in some works (Aziz, 2000; López, 2010) as a possible third target in the Murzuq Basin.

Seals:

The Palaeozoic sedimentary infill of the Murzuq Basin contains up to seven thick, laterally continuous shaly units able to sealing, although the seal quality of these seven units result variable. The potential seal units are (Fig. 91) from older to younger: The late Ordovician Melaz Suqran and Bir Tlacsin, the early Silurian Tanezzuft, the early Devonian Wan Kasa, the late Devonian Awainat Wanin, the eraly Carboniferous Marar and the late Carboniferous-early Permian Tiguentounine formations. According to the above exposed in section 6, only the shales of the marine Tanezzuft Formation have been reported as effective top seal, and all the commercial finds in the Murzuq Basin have the thick Tanezzuft Formation as top seal. Although the sealing quality of the Formation is good, does to the lateral facies changes the formation becomes sandy towards the South and East, and their sealing capacity diminishes in these directions. In general, the most fine-grained and silty Tanezzuft composition and therefore with better sealing capacity correspond with the central and northern parts of the Murzuq Basin. In some areas where the Caledonian unconformity eroded the Silurian sequence, the middle-late Devonian shales of the Awainat Wanin Formation also contributed as top seal rock, in this case for secondary, non commercial Devonian plays.

In the late Ordovician plays the silty Melaz Suqran and Bir Tlacsin Formations, deposited filling the topographical lows, provide effective lateral seal.

Traps:

Four trap types have been described in section 6 for the Ordovician reservoirs of the Murzuq Basin: a) Hawaz “buried hills” b) lateral pinch-out of the Mamuniyat sandstones, c) single anticlines, and d) lateral closure by faults types. The first two trap types (buried hills and lateral pinch-outs) are late Ordovician in age; the first one related to the erosional surface developed during the late Ordovician glaciation and the second one is a sedimentary feature of the late Ordovician Mamuniyat sandstones; both are the older traps in the Murzuq Basin. The last two trap types (anticlines and faults) are structures related to Caledonian or Hercynian tectonic phases.

The Hawaz buried hills are the most common trap type for the proven oil accumulations in the Murzuq Basin. It has been reported in plays from concessions NC115, NC168 and 101 (Echikh and Sola, 2000; Craik et al, 2001; Franco et al, 2012). As the Hawaz buried hills are bounded by palaeovalleys filled by the Melaz Suqran, Mamuniyat and Bir Tlacsin fine-grained formations could laterally separate the reservoir sandstones of the Hawaz Formation of the Mamuniyat sandstones, resulting in an unique Hawaz play, on the contrary, if these seal units don’t act as effective lateral seal allowing communication between the Hawaz and Mamuniyat sandstones, both formations can act as reservoir. Respect to the discontinuous Bir Tlacsin Fm, stratigraphically located under the Tanezuft source rocks, it can seal the source to reservoir communication, hampering the oil accumulation, so there are some relation between the presence of the Bir Tlacsin Formation in the subsurface and successful findings in the Murzuq Basin.

In the case of a complete lateral seal by the Melaz Suqran Formation, a pinch-out of the Mamuniyat sandstones against Melaz Shuqran or Bir Tlacsin formations is produced. Pinch-out of the Mamuniyat sandstones are the second trap mechanism producing in the Murzuq Basin. Franco et al. (2012) reported this type of trap from fields in concession NC186.

Pre-Hercynian single anticlines and antiforms generally smooth, with low-relief and small-sized, are the most abundant structural traps in the Murzuq subsurface. The Al Sharara A and B pools occur in simple, low amplitude, four ways dip closures (Craik et al, 2001). This trap type has been also reported by Echikh and Sola (2000) in concessions NC58, NC101 and NC115. Some anticlines have lateral closure by faults; in H- and C-NC115 fields reverse faults contribute to the seal on the eastern flanks of these fields, and the giant Elephant oil field is a combination trap comprising an anticline with dip closure to the north, east and south and bounded to the west by a reverse fault. In general, the N-S and NW-SE trending faults are in compression and provide effective seal.

Oil discoveries in the Murzuq Basin seem to be related to old structures formed in Palaeozoic time, although they continued or rejuvenated during Mesozoic times

Palaeozoic Petroleum Systems:

According to the above exposed, two petroleum systems have been identified in the Murzuq Basin. Both involving the early Silurian Hot Shale source: **a)** A late Ordovician sandstone reservoir-Hot Shale source-Tanezzuft seal system, and **b)** A Devonian sandstone reservoir- Hot Shale source-intra Devonian shales seal system.

a) Late Ordovician sandstone reservoir-Hot Shale source-Tanezzuft seal system:

In the late Ordovician sandstone reservoir-Hot Shale source-Tanezzuft seal system, oil was expelled from the basal Tanezzuft Hot Shales directly into the underlying Hawaz and/or Mamuniyat sandstones, which contain all the discovered oil pools in the Murzuq Basin as well as the greatest number of oil shows. Oil migration was short and reservoir recharge laterally. The essential elements of this prolific petroleum system have been well described, but its geographic limits and processes including the history of petroleum generation and trapping have not been well constrained so far and there are disagreement between the different authors. So, basin modelling carried out by Aziz (2000) for block NC115 indicates that oil generation took place during Carboniferous to Permian times; however Echikh and Sola (2000) propose a late Jurassic to early Cretaceous time span for oil generation. Burial and thermal history proposed by Davidson et al (2000) for NC174 concession indicate that oil generation took place during middle Cretaceous to early Tertiary times. Craik et al. (2001) propose that the main phase for oil generation took place during Jurassic – Cretaceous times, although to the northwestern part of the basin oil generation could be pre Hercinyan. Basin modelling by Franco et al. (2012) suggest that the onset of oil migration is early Triassic in NC186, getting younger towards the east of the concession, and Galushkin et al. (2014) found that oil generation stars during late Carboniferous, but the main phase of oil generation occurred during Tertiary times.

The first evaluation of oil reserves in this petroleum system for the Murzuq Basin is owing to Boote et al (1988), which estimate that the system reservoirs approximately 600 MBOE. Geochemical analysis carried out by Aziz (2000) indicate that in NC115 concession the Hot Shale may have generated approximately 8.3 to 19.4 MBB/km^2, giving the potential for approximate amounts of entrapped hydrocarbons in the Murzuq Basin of around 40 BBB. Later estimations are by Ismail et al (2002) which propose accounts for arround 4000 MBB of proven oil in place in the Murzuq Basin and Craik et al

(2001) which attribute to the Hot Shale-late Ordovician sst. system more than 2000 MMSTB.

This system is the primary play in all the commercial oil discoveries in the northern and central part of the Murzuq Basin.

b) Devonian sst. reservoir- Hot Shale source-intra Devonian shales seal system:

A second possible petroleum system is related to the Devonian sandstones charged by Devonian and/or Silurian organic-rich shales. For Echikh and Sola (2000) this possibility is supported by the discovery of non commercial oil accumulations in wells A1-NC58, A1-76, C1-NC115 and P1-NC101 and by the presence of frequent oil shows in structurally high areas as in wells M1-, E1-, C1-, F1-, and I1- NC101.

The Devonian sandstone reservoir are mainly made by the BDS interval, a regionally continuous shallow marine sandstones grouped into two packages separated by a conspicuous shale interval with a total thickness in NC186 concession of about 70 m (Franco et al, 2012). In concession NC186 very low relief structural closures are present at BDS level making this primarily a stratigraphic play. According to Echikh and Sola (2000), at present the hydrocarbon potential of the Devonian sandstone reservoir – Hot Shale source system in the Murzuq Basin (distribution of good quality sand, migration and trapping of hydrocarbons) remains poorly understood. The presence of good quality reservoirs and of proven Devonian source rocks, locally with a high TOC reaching 2% to 4% (e.g. A1-NC58, and A1-NC34) makes this play a promising future target, particularly in more shaly areas of the Murzuq Basin, where good seals are also expected to be present to cap these Devonian sandstone units.

The Devonian-Silurian petroleum system efficiency may be limited by the high risk associated with migrating hydrocarbons up the thick Tanezzuft shale section into the Devonian reservoirs without the presence of faults. This system would be more significant if a Devonian source rock is proven to exist (Ismail et al, 2002).

8. CONCLUSSIONS

In this Thesis a number of concluding remarks have been achieved. These conclusions refers to different aspects regarding the stratigraphy and sedimentary infill of the basin, the source rocks and time of oil generation, reservoir and seal rocks, the type and age of the traps and the potential petroleum systems. There are the following:

Stratigraphy and sedimentary infill:

The present-day Murzuq Basin is an erosional remnant of a much larger continental margin rimming Gondwanaland during Palaeozoic times. The present-day borders of the basin are defined by erosion resulting from various tectonic events ranging from Middle Paleozoic to Tertiary in age.

The base of the Palaeozoic succession is the Pan-African unconformity, separating the Palaeozoic sequence of an early Cambrian to Mesoproterozoic basement. The Palaeozoic succession of the Murzuq Basin is relatively continuous, recording a time-span from early Cambrian to early Permian times. In the depocenter the Palaeozoic sequence is more than 3000 m thick.

The Palaeozoic succession is subdivided in fifteen lithostratigraphic units recording deposition in marine to transitional settings.

Three main basin-scale unconformities are recognized within the Palaeozoic sequence. These unconformities are late Ordovician, early Devonian and late Carboniferous to early Permian in age. The first one is related to the late Ordovician glaciation, and the last two are related to the Caledonian and Hercynian tectonic phases. These unconformities allow us to group the stratigraphic units into four second order sequences.

Among the fifteen lithostratigraphic units constituting the Palaeozoic record of the Murzuq Basin there are units having good properties as source, reservoir or seal rocks. The best source rock is the early Silurian Hot Shale Mb at the base of the Tanezzuft Fm; a secondary potential source rock is the organic-rich shaly intervals of the Awainat Wanin Fm (late Devonian). Good porosity and permeability values characterize the sandy late Ordovician Hawaz and Mamuniyat formations; the middle Devonian BDS interval also has good reservoir properties. Although there are a number of silty units with capability to seal, the main cap seal in the Basin correspond with the thick early Silurian Tanezzuft Fm, although the late Ordovician Melaz Suqran and Bir Tlacsin Fms also contribute to lateral sealing.

Source rocks, maduration and timing of oil generation:

All the commercial findings in the Murzuq Basin were sourced from the early Silurian Hot Shale Mb. It is the most prolific source rock in the basin and reported the highest TOC values, ranging from 2.0 to 23.3%.

The Hot Shale samples have good pyrolisis-related hydrocarbon generative potential parameters such as S2 and Hydrogen index (HI). Hydrogen Index values range between 50 and 400, although most of the samples have values lowers than 175. Usually S2 values reach up to at least 60 mg HC/g rock and probably up to 100 mg HC/g rock for the best samples, both indicative of a rich source rock.

Rock-eval pyrolisis of Hot Shale samples supplied Tmax values falling in the oil window (430-446º C range) for most of them, although few samples have Tmax values lower than 430º C indicating inmature to early mature conditions for oil generation.

Hot Shale maturity is also supported by vitrinite reflectance data with the most of the samples reaching from 0.5 to 1.4 %Ro and only the shallower samples falling into the immature field, with Ro<0.5%.

The organic-rich Hot Shales facies contain mainly type II oil-prone kerogen. The main kerogen component is amorphous organic matter (AOM), reaching up to the 80%. Kerogen rich in AOM typically characterizes a type II kerogen

There is not agreement about the timing of oil generation and primary migration from the Hot Shale in the Murzuq Basin. Diverse basin modelling carried out by different authors assuming different inputs for their models find timing of oil generation from Carboniferous to Jurassic, Cretaceous or even Cenozoic times. Most of this disagreement is related to differences in the role played by Caledonian and Hercynian uplifts and denudation, Mesozoic burial and Tertiary Alpine deformation; thermal history of the basin is also a key input remaining uncertain. Future works must be addressed to constrain the parameters to be used for modelling.

The Palaeozoic oils of the Murzuq Basin are light oils, with API degrees ranging between 31.8 and 40.9.

A secondary source rock in the Basin is the organic-rich shaly intervals of the late Devonian Awainat Wanin Formation.

TOC analyses of the Awainat Wanin samples have TOC contents up to 6% and S2 up to 15 mgHC/g rock for the best samples. However these samples are usually inmature to early mature and their source potential is speculative.

Awainat Wanin samples contain kerogen type II/III grading to type II kerogen.

Reservoirs:

Two reservoir rocks with good porosity and permeability values have been defined in the subsurface of the Murzuq Basin. There are the late Ordovician Hawaz and Mamuniyat sandstones and the middle Devonian BDS interval.

The late Ordovician sandstones are the most prolific reservoirs in the subsurface of the Murzuq Basin and all the commercial findings in the basin are reservoired within these sequences. The Basal Devonian Sandstones (BDS) only acts as a reservoir unit locally and it is considered as a secondary play with non commercial findings. Other detrital units with moderate porosity and permeability values have been not proven as reservoir.

The role played by the late Ordovician Hawaz and Mamuniyat sandstones as the main reservoir units in the Murzuq Basin is related not only to their moderate to good reservoir properties, but also to their stratigraphic position.

The late Ordovician Hawaz and Mamuniyat sandy formations are separated by erosive surfaces forming paleoreliefs, which provide lateral contact with the Hot Shale source rocks allowing their lateral recharge. In turn, the thick overlaying Tanezzuft Fm which acts as the main top seal, prevent hydrocarbon migration from the basal Hot Shale to the overlying siliciclastic units.

Core plug samples of the Hawaz sandstones reported porosity values ranging between 5.0 and 27.5% (average 15.7%) with pore diameter ranging from 0.1 μm to 64 μm (average 14.6 μm). Pore connectivity appears to be good, mainly in sandstones with total porosity greater than 8%. Permeability is moderate to good, with values reaching up to 800 mD (average 30.5 mD). Porosity includes primary intergranular and secondary intragranular, mouldic and microfracture pores.

In subsurface primary porosity of the Hawaz sandstones is reduced by early diagenetic kaolinite and pyrite formation and mechanical compaction; at deep burial conditions quartz overgrowth, illite formation and chemical compaction took place by mesodiagenetical processes

The porosity of the Mamuniyat sandstones has a great variability as a result of the rapid facies variation in the Formation. The lowermost porosity correspond with the central Murzuq, were usually it is lower than 5%. Porosity increases westwards reaching their maximum values (20 – 25%) near Ghat. Towards the north, south and east the trend of the porosity increase is lower. Permeability is moderate to good, with values reaching up to 1850 mD (average 175 mD). The main porosity type is the primary intergranular; although in some areas secondary feldspar dissolution, fracture and microfracture porosity has been reported enhancing total porosity.

The primary porosity of the Mamuniyat sandstones is reduced by secondary factors, which tend to reduce the reservoir quality through compaction and precipitation of authigenic quartz cement and kaolinite.

Seals:

The sealing properties of the Tanezufft shales are generally good, mainly in distal areas where their basal Hot Shale Mb, recording deposition in deep marine environments exists, as in the north, northwestern and central parts of the basin. All the commercial finds in these Murzuq areas have the thick and shaly Tanezzuft Fm as top seal.

Only in areas were the Tanezzuft Fm thins (on major paleohighs) or becomes sandy (south and eastwards), their sealing properties worsen.

Lateral seal in the north, northwestern and central Murzuq is provided by the fine-grained low permeability strata of the late Ordovician Melaz Suqran and Bir Tlacsin Formations.

In some localities the Devonian Awainat Wanin shales also contributed as top seal rock for secondary (Devonian) non commercial plays.

The lateral continuity of the sealing surface, in addition to other factors such as lateral permeability and fault barriers, are the main parameters controlling migration pathways.

Traps:

The most pervasive trap type is the called “Buried hills”, a geomorphological feature glacially related that provide effective traps for most of the proven oil accumulations.

Buried hills are the oldest traps currently producing oil in the Murzuq Basin.

Other more subtle traps related to anticlines, faulted anticlines, stratigraphic truncation and permeability barriers may also occur.

Palaeozoic petroleum systems:

The primary play in all the commercial oil discoveries in the northern and central part of the Murzuq Basin is constituted by the late Ordovician sandstones reservoir – Hot Shale source – Tanezzuft seal petroleum system. About 4000 MBB of proven oil in place are proposed for the Murzuq Basin.

Most of the commercial findings are confined to areas with extensive palaeohighs, thick Hawaz or Mamuniyat sandstone sequences, rich mature Hot Shale, thick Tanezzuft top seal and thin – or absent – Bir Tlacsin Fm.

A possible second play may be constituted by BDS sandstones reservoir – Hot Shale source – Intra Devonian shales seal petroleum system. This possibility is supported by the discovery of non commercial oil accumulations in concessions 76, NC58, NC115 and NC101.

Although Devonian petroleum system has not yet been proved as a commercial play, it may have a promising potential, particularly in areas where BDS reservoir have good shale seal.

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