DEPOSITIONAL ENVIRONMENTS OF THE UPPER ORDOVICIAN, MAMUNIYAT FORMATION, NW MURZUQ BASIN, SW LIBYA

Nuri Mohamed Fello*

Abstract: The Murzuq Basin, SW Libya, is one of a series of Palaeozoic intracratonic sag basins on the North African Saharan Platform. The structural fabric of the basin was developed during the Late Proterozoic Pan-African Orogenic event, which has strongly influenced the stratigraphy and depositional patterns within the predominantly Palaeozoic clastic basin-fill.

The Upper Ordovician (Ashgillian) Mamuniyat Formation is the primary reservoir target in three oilfields A, B and H within Repsol Oil Operations Concession area NC115, on the NW flank of the Murzuq Basin. A major problem with the Mamuniyat is the location of the sediment provenance, due to the lack of adequate subsurface and outcrop data, and the relationship and controls on sediment flux, and the depositional systems. Petrographic data derived from sandstone samples from cored intervals through the Mamuniyat Formation show that they are mainly sublitharenites, with some quartz arenites and litharenites. Compositional data for the three oilfields indicate that they were derived from a similar parent rock. These same tectonic events influenced facies patterns, sediment deposition and interaction between a variety of shallow water marine and fluvial depositional environments across a NW-SE oriented storm-influenced coastline. Petrography and regional facies patterns suggest that the Mamuniyat sandstones were derived from a nearby, tectonically active, granitic basement source terrain, which was most probably the uplifted Ghat/Tikiumit Arch to the SW of NC 115. Periodic uplift of the basin margin in the SW, and associated base level changes led to the basinward progradation of braided fluvial systems. That was followed by marine transgressive events emanating from Palaeotethys in the northeast. Both the braided fluvial and shallow water marine sandstones of the Mamuniyat Formation are primary hydrocarbon reservoir targets, with the main source and seal being the eustatically controlled Lower Silurian Tanezzuft Shale.

Keywords: Ordovician Succession, Mamuniyat Formation, Murzuq Basin, SW Libya.

INTRODUCTION

The Murzuq Basin of SW Libya (Fig. 1) forms one of a series of Palaeozoic intracratonic sag basins on the Saharan Platform. The structural fabric, imposed on the North Africa continental lithosphere during the Late Proterozoic Pan-African Orogenic event, played an important role in controlling subsequent structural and stratigraphic evolution of the basin (Thomas, 1995). The basin, which covers an area of some 350,000km2, is sub-circular in shape and clearly visible on satellite photographs of SW Libya. During Early Palaeozoic times, NNW trending horst and graben structures developed, which extended as far as the eastern Ennedi Mountains in Chad and the northern and central parts of Niger. The horst and graben structures are filled with siliciclastic continental and shallow water marine sediments (Klitzsch, 2000).

Thus, Early Palaeozoic tectonism effectively controlled the distribution of the main fluvial-shallow marine reservoir interval of Upper Ordovician (Ashgillian) age, in several oil fields. The Murzuq

Basin is a Palaeozoic structural element filled with strata of Cambrian to Carboniferous age, including several hundred meters of Lower Silurian Tanezzuft Shale that locally has excellent to fair source rock potential (Fello and Turner, 2001).

Repsol's NC115 Concession, which lies on the northwest flank of the Murzuq Basin, is located

*National Oil Corporation, Exploration Department, P.O. Box: 2655, Tripoli – Libya. E-mail address: nfello@noc.ly

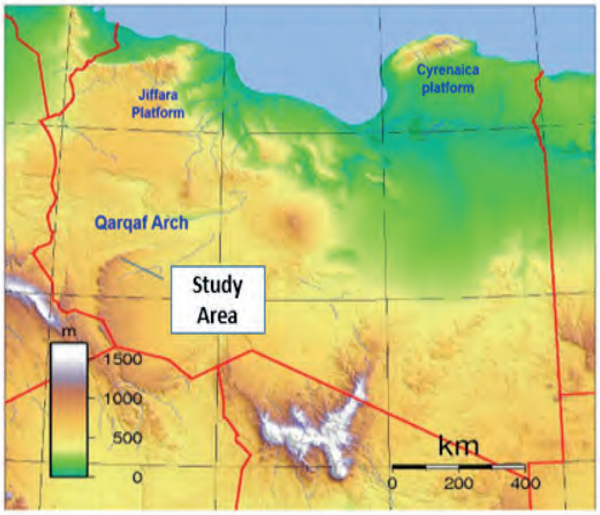

Fig. 1. Location map of the study area in NW Murzuq Basin, SW Libya.

some 1,330 km SW of Tripoli and covers an area of 25,850 km2. The main focus of this study is the Upper Ordovician (Ashgillian) Mamuniyat Formation, which is the primary reservoir target in three oilfields A, B and H within the Repsol Concession area NC115 (Fig. 2). The subsurface occurrence of the Mamuniyat sandstone is 20-170m thick, but with a regional thickening towards the northeast towards the Gargaf Arch (Pierobon, 1991).

A problem with the Mamuniyat Formation is the location of the sediment provenance, and the relationship and controls on sediment flux and the depositional systems, due to the lack of adequate subsurface and outcrop data. This study is based on core photographs and samples from more than 310m (1016ft) of conventional core from 12 oil wells distributed throughout the three oilfields A, B and H (Fig. 2). Wells A8, B2 and H4-NC115 are type section wells, which provide core coverage of the Mamuniyat Formation of over 134m in A8-NC115, 126m in B2-NC115 and 54m in H4-NC115. In addition we have also worked on a number of additional exploration and development oil wells, to provide further information and constraints on lateral facies variations between the three main oilfields.

STRATIGRAPHIC FRAMEWORK

The Murzuq Basin succession unconformably overlies Precambrian crystalline basement. It consists predominantly of Palaeozoic sediments with lesser amounts of Mesozoic and Cenozoic sediments (Fig. 2), which attain a maximum thickness in the central part of the basin of over 3500m. However, the complete succession is only preserved at outcrop in a few areas due to regional erosion during the Caledonian and Hercynian Orogenic events. The present structural framework of the basin is largely a result of successive, superimposed tectonic events related to the Taconic, Caledonian and Hercynian orogenies. Although tectonic activity continued to influence the basin until post Eocene times (Fig. 3). As a result the basin exhibits a variety of structural styles, fault patterns and traps. The early to mid Palaeozoic structural relief comprises a system of NNW to N striking horst troughs developed during Cambrian to Early Ordovician times. These form wide elongate troughs that became the routes for long-distance transgression to the south or southeast, whenever the northern part of Gondwana was transgressed by the sea.

Consequently, these structurally low areas were covered by relatively thick sequences of marine strata during highstand, whereas during periods of regression, they become the sites of nearshore marine or continental sedimentation. In contrast intervening uplifted horst areas were subject to reduced sedimentation and/or erosion (Klitzsch, 2000).

SEDIMANTARY FACIES ASSOCIATIONS AND ENVIRONMENTS

The Mamuniyat Formation can be divided into three main facies associations, each of which comprises a number of constituent facies, defined on the basis of their lithology, sedimentary structures and trace fossils. These facies associations are interpreted to represent two main depositional environments: braided fluvial and marine (Fello,

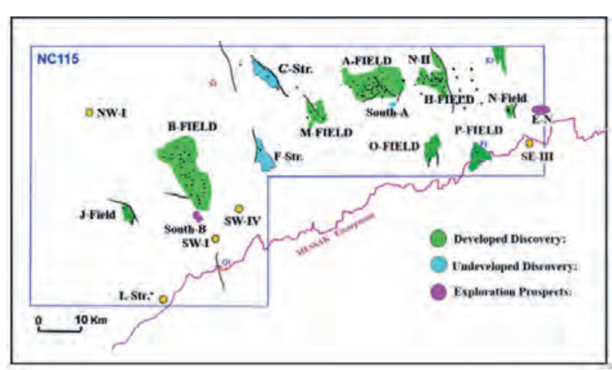

Fig. 2. Location map of the main oil fields in NC115 Concession, Murzuq Basin.

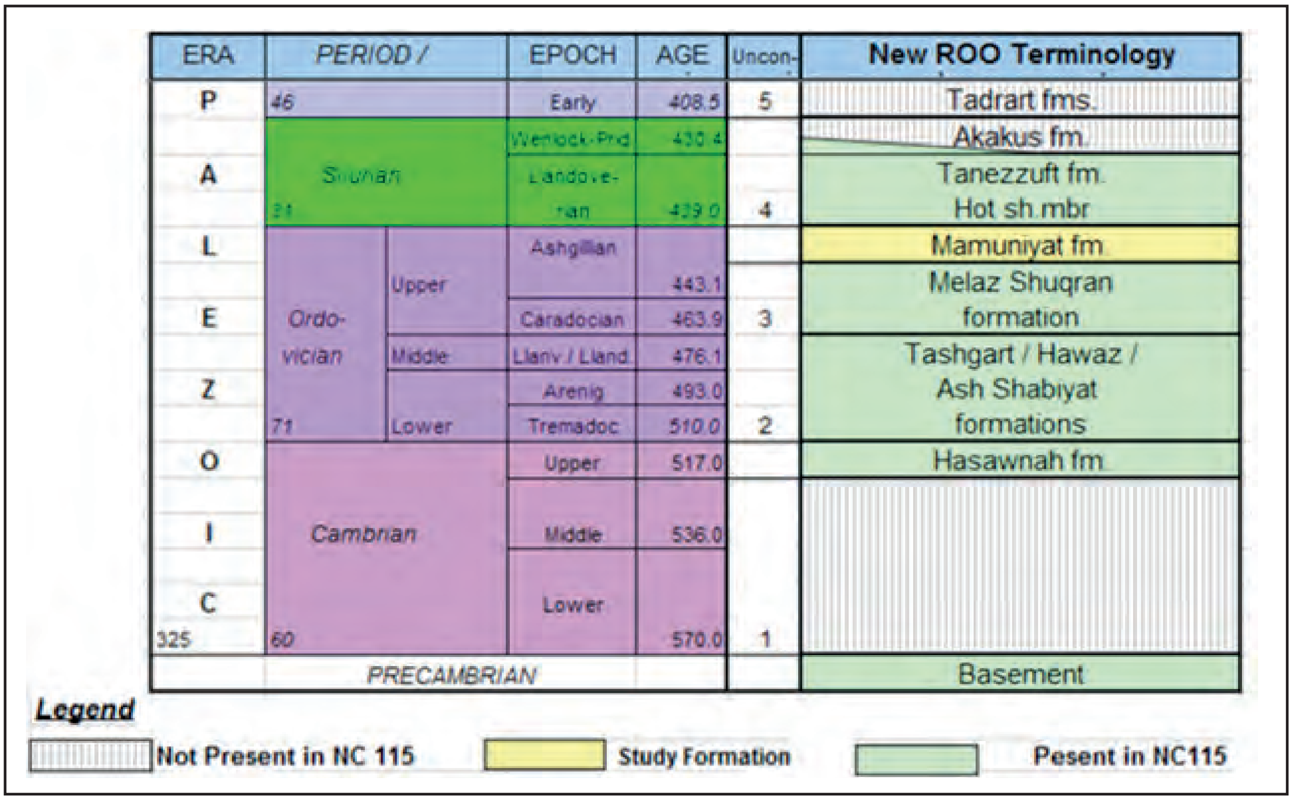

Fig. 3. Stratigraphic column of the study section within NC115 area, NW Murzuq Basin, SW Libya.

2001). Fig. 4 summarises the facies associations, their constituent facies, and depositional environments. The facies associations are described and interpreted below based on the terminology of Miall (1996).

Alluvial Plain Facies Association

Description: This facies association is restricted to the Upper Member (M1) of the Mamuniyat Formation (Fig. 4) in the southwest part of NC115 Concession.

It is restricted to the B-Field where it makes up most of the reservoir interval, especially in type well B2-NC115 (Fig. 2). This facies association is represented by the cored interval from 1402m to 1430 m. It is represented by course- to very coarse-grained sandstone with rare coarse-grained siltstone interbeds. The sandstones are poorly sorted, and mainly sublitharenite in composition. A characteristic feature of this facies association is that it forms thick packages of sandstone beds ranging from 10cm to 15cm in thickness, which show a fining-upward trend from very coarse and coarse-grained sandstone to very coarse and medium-grained sandstone (Fig. 4). The dominant sandstones, and individual beds of siltstone can be traced throughout all the wells in the B-Field (32 wells), over a distance of some 10km. Two locally developed types of fining-upward sequence occur as following:

1) Scoured, intraclast-strewn surface, overlain by coarse- to very coarse-grained, medium- to small-scale trough cross-bedded sandstone passing up into fine-grained ripple cross-laminated and horizontally-laminated sandstone with some siltstone; and
2) Medium- to fine-grained, large-scale planar cross-bedded sandstone in which individual sets decrease in scale upwards are overlain by fine-grained sandstone containing small trough cross-bedding. The sandstone beds show an upward increase in thickness with a concomitant decrease in the abundance of pebbles, horizontal lamination and ripple cross-lamination, which is confined to the upper part of the sandstone beds.

The sedimentary structures are dominated by medium-scale, trough cross-bedding from 10 to 25cm thick. Soft sediment deformation structures are rare, but some laterally more continuous horizons showing fluid escape structures are common in the southwest part of the study area in the B-Field (Fig. 2). Some sandstones contain

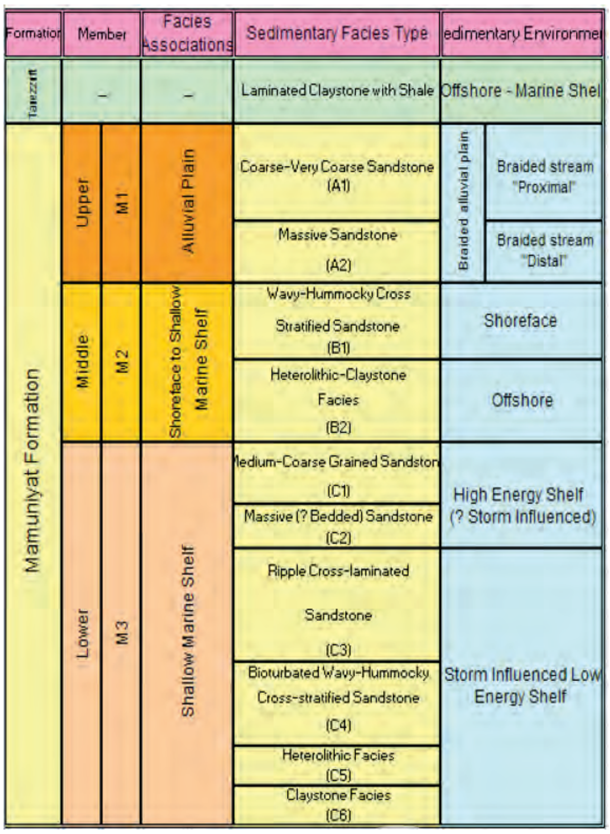

Fig. 4. General characteristics of the fluvial and shallow marine facies within the Mamuniyat Formation, NC115 Concession.

low-angle truncation surfaces that can be traced laterally for several tens of metres, as well as laterally discontinuous minor erosional scour surfaces. In addition, the rare micaceous siltstone units form laterally discontinuous lenses, and contain *Tigillites* burrow forms incised by the sandstones.

In the lowermost part of the alluvial plain facies association, the sandstone is mostly structureless and sedimentary structures are very rare, where present they consist of planar and trough cross-bedding, flat bedding and ripple cross-lamination with individual ripple sets from 0.02m to 0.5m thick. Flame structures are also present and rare subvertical fractures, possibly enhanced by coring, which were open to silica cement. Moreover, the sandstones also contain a few stylolites with the orientation of some of the sutured seams generally parallel to bedding. Thus, the stylolite axes are perpendicular to the primary bedding surface (Bauerle *et al*, 2000). The thinly bedded siltstones, which range from 1cm to 5cm in thickness, are mainly confined to the lowermost part of this facies association, and contain sub-angular to sub-rounded intraclasts of fine to medium-grained sandstone.

Interpretation: The coarse-grain size, planar and trough cross-bedding, small fining-upward and coarsening-upward sequences within multistoried, truncated packages are most consistent with a braided fluvial depositional environment for this facies association.

Direct analogous outcrops of this facies association have not been found in the SW Murzuq Basin (Herzog, 1997). The upward increase in bed thickness, grain-size, and the scale of cross-bedding provides a measure of proximity to detrital clastic influx and the source area. The fine- to medium-grain size, better sorting and limited thickness of the sandstones within the lower part, compared to the upper part, suggest that the sedimentary properties of the sandstone change continuously away from the basin edge. Enabling the depositional setting of the Upper Mamuniyat Formation to be divided into an upper braided plain (proximal) and lower braided plain (distal). The lowermost part of the Upper Mamuniyat sandstone was deposited in a zone of decreased gradient and stream power with increased entrapment of fine-grained detritus. This suggests that they were deposited further away from the source area than the uppermost part of the Upper Mamuniyat Formation. However, the textural uniformity of the sandstones could be related to the nature of the sediment available at the source area (Ghat/Tikiumit Arch) located to the southwest of NC115 Concession.

The sedimentary structures and alluvial architecture of this facies association are similar to those observed in the Platte-type and shallow, perennial, sandbed braided river models of Miall (1996). This interpretation is consistent with the abrupt transition from very coarse-grained to medium-grained sandstone, the low ratio of siltstone to sandstone and lack of fossils. Intimate interbedding of pebbly sandstone and coarse to very coarse sandstone, plus the occasional presence of thin siltstones within the upper part indicate that changes in discharge were both frequent and extreme. In the Upper Member of the Mamuniyat Formation, the grain-size variations within lenticular beds indicate lateral as well as vertical changes in current velocities (Fello and Turner, 2001). The presence of a monotypic *Tigillites* ichnofabric in the alluvial plain facies association may indicate the periodic establishment of paralic environmental conditions. However, present data is extremely limited and the significance and regional extent of this ichnofabric is uncertain.

The variation in thickness of the sandstone is probably a function of temporal fluctuations in flow regime and flow depth during deposition. The overall lithological characteristic patterns of sedimentation and lack of evidence of subaerial exposure are consistent with a year round rainfall, relatively high runoff, and perennial braided streams.

Shoreface to Shallow Marine Shelf Facies Association

Description: This facies association has been found only in the southwest part of the study area within the B-Field. It is restricted to the middle Member (M2) of the Mamuniyat Formation (Fig. 4). This facies association is represented by the cored interval from 1430m to 1456m in type well B2-NC115. The entire thickness is about 26m, and comprises fine- to medium-grained sandstones with black shales (Fig. 4).

The uppermost part of this facies association is dominated by hummocky cross-stratified sandstone (HCS), particularly in type section well B2-NC115 (Fig. 3). The HCS consists of fine-to medium-grained sandstone and is generally overlain by concordant laminae, with interbedded cross-bedding and ripple-cross laminated sandstone. Internally, the HCS sandstones are coarse-grained and display flat, low angle cross-bedding, which can be braced laterally for hundreds of meters within the B-Field (Herzog, 1997). Glauconitic sandstone, an important constituent of the fine-grained sandstones, is found associated with the hummocky cross-stratified package in the middle Mamuniyat Formation. The HCS sandstone beds are usually sharply based, sometimes with small-scale scours and erosion into the underlying sandstone. The position of the hummocks above erosional depressions is similar to the stratification described by Surlyk and Noe-Nygaard (1991) from Jurassic sandstones in Denmark. Furthermore, the HCS sandstones contain sparse *Cruziana* bioturbation and vertical burrows (? *Skolithos*). These burrows occur mostly as narrow tubes up to 3cm long and 2mm wide. The most characteristic burrows are *Tigillites* (Selley, 1996). The lowermost part of the middle Mamuniyat Formation (M2) is dominated by heterolithic-claystone, particularly in type section well B2-NC115. It is mainly composed of black shale (Radioactive Shale) and subordinate fine-grained sandstones with rare coarse-grained siltstone (Fello, 2001).

The black shales are intercalated with wavy, rippled, light grey to reddish-brown siltstone to fine-grained sandstone beds. The entire succession shows a general fining-upward trend and passes sharply upwards into fine-grained-sandstone, siltstone and shale. The black shales are well compacted/indurated, carbonaceous, micaceous, and fissile, and form laminae-sets 0.5cm to 3cm thick. The heterolithic-claystone forms beds, which range from 5cm to 10cm in thickness. These are tabular and sharply based, with small-scale ripple and/or parallel-laminations. Furthermore, the intense bioturbation throughout the heterolithic-claystone, has destroyed the primary structures and homogenized the sediment. The heterolithic-claystone also contains plant material preserved on lamination planes parallel to fissility (Fello and Turner, 2001).

Interpretation: The wavy-hummocky cross-stratified sandstone is interpreted as the middle/intermediate shoreface of a nearshore zone, influenced by two alternate hydraulic regimes; traction and suspension (Ghosh, 1991). The HCS is thought to result from episodic storm wave activity and wave-generated surges. Variations of the HCS beds described herein can be explained in terms of amalgamated HCS. The various features of the HCS were produced by both oscillatory and combined oscillatory/unidirectional flows that prevailed during various stages of individual storms (Cheel and Leckie, 1992). The abundance and orientation of cross-bedding point to deposition from low flow regime traction currents. The fine grain-size, however, shows these currents to have had significantly lower velocities than those which deposited the overlying braided alluvial plain sandstones of the alluvial plain facies association. The occurrence of tabular planar cross-beds and the absence of channelling indicate that these were open flow currents not confined by channel banks.

Both vertical *Skolithos* burrows, *Cruziana* and the *Tigillites* ichnofacies, indicate that deposition occurred in a shallow marine setting. The medium-grained sandstone with occasional coarse-grained siltstones and some fine glauconitic sandstone within the wavy-hummocky cross-stratified sandstone are interpreted as storm- and wave dominated shelf sediments deposited near fair-weather wave base. The scarcity of wave-produced features suggests relatively minor wave influence between storm events (Selley, 1996). The offshore shallow marine environment is sedimentologically complex because of the number of different processes, which operate within it. Relative to other sediment, the products of these processes are poorly known because of the physical difficulties involved in studying them and because of the present disequilibrium of continental shelves. On the NW flank of the Murzuq Basin, particularly in the B-field, the highly radioactive shales in the middle Mamuniyat Member, are mainly confined to localized palaeotopographic lows (valleys, erosional or structural depressions) or to broad areas flanking highs such as in the A and H-Fields in the northeast part of Concession NC115 (Fello, 2001).

Shallow Marine Shelf Facies Association

Description: This facies association forms the bulk of the lower Mamuniyat Formation (M3, Fig. 3). It occurs in the three oilfields of the study area, and is represented by the cored interval from 1408m to 1541m in type well A8-NC115, the cored interval from 1456m to 1528m in type well B2-NC115 and the cored interval from 1475m to 1529m in type well H4-NC115. The entire facies association comprises sandstone, characterized by a coarsening-upward trend marked by alternations of fine- to medium-grained and minor coarse-grained sandstone, and subordinate coarse-grain siltstone with claystone. The uppermost part of this facies association consists of medium- to coarse-grained, mostly sublitharenite sandstone, which locally contains small amounts of glauconite. Massive sandstones beds occur within 12m thick succession, which comprises less than 10% of the facies association. The individual beds of massive sandstone are often structureless in appearance, and generally homogeneous, occasionally exhibiting pebbly-stringers and indistinct lamination. The whole succession is referred to as the massive sandstone complex. The middle part of this facies association contains ripple cross-lamination and bioturbated sandstone beds. In the ripple cross-laminated sandstone the amount of burrows normally increases upward. The burrows are predominantly horizontal, < 1cm in diameter, and filled with light grey siltstone and/or very fine sandstone. Moreover, a few small narrow vertical burrows, < 1cm long, belonging to the *Skolithos* and *Cruziana* ichnofacies, also occur in the sandstone (1457m in type well B2-NC115). The lowermost part of the Mamuniyat Formation mainly consists of claystone deposits. This interval of claystone exhibits soft-sediment deformation structures. However, bioturbation is locally present in this succession and decreases upward concomitant with increased parallel lamination (Fello, 2001).

Interpretation: The alternation of fine-to medium-grained sandstones with coarse-grained siltstone and claystone throughout the lower Mamuniyat Formation shows that the environment was one of fluctuating current strengths. Mud, silt, and probably some of the thinnest sand laminae were deposited directly from suspension, but in the thicker sandstones bedload transport resulted in the development of bedforms, and primary sedimentary structures (Fig. 5). The absence of high angle cross-stratification in the fine-grained sandstones may be due to the narrow range of flow power, especially under condition of decreasing current strength.

Medium- to coarse-grained sandstone shows a range of storm-generated wave and current features, which indicate that the normal, quieter background sedimentation was overprinted by episodic storm conditions. Vertical changes in sedimentary structures and grain-size indicate changes in wave and current energy (Turner, 1980). The individual shale beds within the lower Mamuniyat Formation may have formed during a minor transgression and increased water depth. Ripple cross-lamination is the dominant physical sedimentary structure formed in the nearshore according to Fello (2001). The most common situation is one of ripple cross-laminated sandstone intercalated with siltstones and shales. The interlaminated sandstone and shale beds suggest variable depositional conditions and periodic higher energy currents affecting a normally quiet-water environment (Hein *et al*, 1991). The abundance of *Skolithos* and *Cruziana* within ripple cross-laminated sandstone indicate that deposition occurred in a

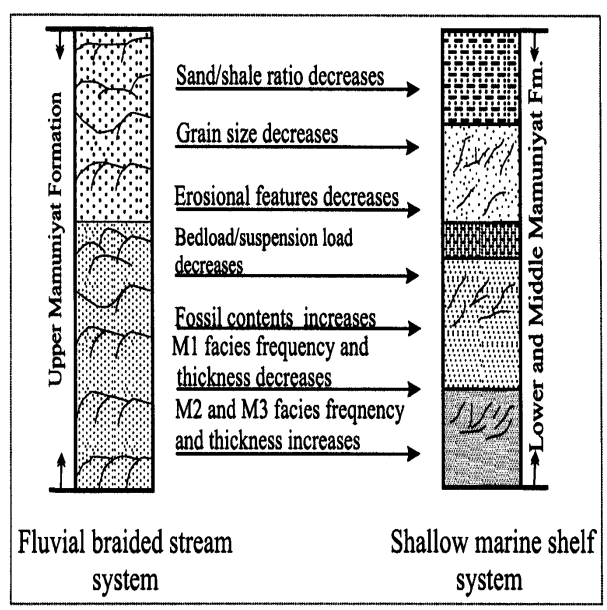

Fig. 5. General characteristics of the fluvial and shallow marine facies within the Mamuniyat Formation NC115 Concession.

shallow marine setting. As noted by Fello (2001), the abundance of fine glauconitic sandstone is also a good indication of marine setting. The occurrence of burrowing and bioturbation within wavy-hummocky cross-stratified sandstone suggests a more-protected environment, possibly periods of reduced current activity with alternations of current and biogenic structures related to their differential energy level. The contact between the bioturbated sandstone and the wavy-hummocky cross-stratified sandstone is interpreted to represent fair-weather wave base of the shallow marine environment, with the presence of bioturbation indicating a relatively low-energy environment with slow rate of sediment input (Fig 5). Claystone deposits show subtle changes in colour from darker shale to lighter sandstone/siltstone indicating periodic changes in sedimentation rates from relatively slow to fast. Furthermore, the laminae commonly have sharp bases and locally diffuse tops, features characteristic of shelf storm deposits.

DEPOSITIONAL MODEL

Depositional conditions were variable during deposition of the Upper Ordovician (Ashgillian) Mamuniyat sandstones on the northwest flank of the Murzuq Basin, particularly the increasingly continental aspect of the facies associations upwards through the succession; a factor which has left its impact on both source and reservoir potential. The basement rocks of the massif areas surrounding the southwestern part of the study area appear to have acted as a clastic source for the Mamuniyat Formation and were only intermittently reached by marine transgressive events from Palaeotethys in the northeast. Based on facies associations the Mamuniyat Formation on the NW flank of the Murzuq Basin is interpreted to have been deposited in braided fluvial and marine depositional environments (Fello and Turner, 2001).

The Mamuniyat sandstones display seaward progradation (coarsening-upward package), and basinward-thinning (clastic wedge) to the northeast, accompanied by a change from fluvial to marginal marine and neritic marine environments. Significant thickness variations reflect a strong tectonic control on sedimentation (Thomas, 1995; Fello, 2001). Laterally the Mamuniyat sandstone shows changes in grain-size, lithology and sedimentary structures. These changes are fundamentally linked to the gradient decrease in passing outward from the source terrain, with concomitant decrease in stream capacity and competence. Although the sedimentary properties change continuously away from the basin edge, the depositional setting of the Mamuniyat Formation can be divided into an upper braidplain (proximal), a lower braidplain (distal), shallow marine shelf and nearshore marine environment (Fig. 6).

CONCLUSION

1- Deposition of the Upper Ordovician (Ashgillian) Mamuniyat Formation on the NW flank of Murzuq Basin occurred within a braided alluvial plain and shallow marine setting. Repetition of fluvial and marine sandstones is attributed to interaction of the fluvial and marine environments cross a NW-SE oriented coastline in response to episodes of progradation and transgression.
2- The NC115 Concession is unlike other Palaeozoic basins in Libya in that, there is no direct evidence of a glacial influence on deposition during Upper Ordovician (Ashgillian) times (Turner, 1980; Fello, 2001).
3- Compositional data indicates that the Mamuniyat sandstones in the three oilfields, were derived from a similar parent rock, but with differences in modal composition, textural attributes and porosity of the lower, middle and upper Members of the Mamuniyat Formation. This is attributed to tectonic activity and source area uplift.
4- Facies associations suggest that these same tectonic events also influenced sediment deposition and interaction between shallow marine and fluvial depositional systems, with the

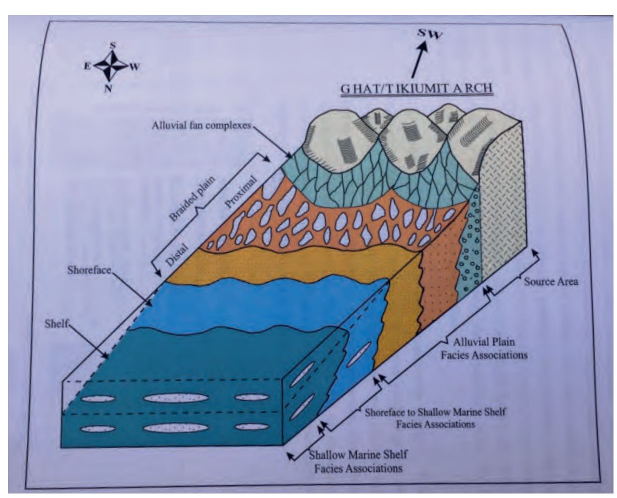

Fig. 6. General Depositional Model for Upper Ordovician, Mamuniyat Formation, NC115 Concession, NW Murzuq Basin, SW Libya.

marine shelf subjected to frequent storms (Fello and Turner, 2001). The Mamuniyat sandstones were derived from a nearby, tectonically active, granitic basement source terrain, which was most probably the uplifted Ghat/Tikiumit Arch some 150km to the SW of NC 115 Concession.

5- The Upper Ordovician Sequence (Ashgillian) Mamuniyat Formation shows an increased marine influence toward the northeast. It is dominated by proximal braided stream deposits in the southwest giving way to fluvial-marginal marine and shelf deposits in the northeast. Poor correlation within the Mamuniyat sandstone is a function of its complex stratigraphy, due mainly to a series of rapid, changes in sea-level and increases in regional tectonism (Fello, 2001).

ACKNOWLEDGEMENT

This paper is based on part of the main author Ph.D. Thesis submitted to the University of Durham, United Kingdom. Sincere appreciation is expressed to my supervisor Dr. Brian Turner for his assistance throughout the project. Dr. Fello should also like to thank the National Oil Corporation and Akakus Oil Operations (Repsol), for their financial support and encouragement throughout this study, and for permission to publish the results of this work.

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