International Journal of Science and Research (IJSR)
ISSN: 2319-7064
ResearchGate Impact Factor (2018): 0.28 | SJIF (2018): 7.426

Sedimentary Facies and Depositional Environments of the Upper Palaeocene Harash Formation, Nasser Field, Sirt Basin, Libya

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Abstract: ***The sedimentary succession of the Sirt Basin reflects its tectonic and structural evolution, which is closely related to the opening of the Atlantic Ocean and the convergence of Tethys in Mesozoic and Tertiary times. Sedimentation during the Upper Palaeocene-Lower Eocene in the central and western Sirt Basin was characterized broadly by shallow-marine carbonates. Six major carbonate lithofacies have been identified within the Landenian/Ypresian carbonate succession in the study area, and these range from mud-supported carbonates to grain-dominated facies, and are interpreted as predominantly deposited under shallow-marine conditions, within the photic zone, as indicated from their richness in phototrophic fauna and flora (thickness ~ 94-169ft / 29-52m). These include restricted marine environment and more open shallow-marine environment and are interpreted as a carbonate platform developed in a homoclinal ramp situation. The type and distribution of the Harash depositional facies were influenced by basin-floor architecture and environmental controls. Porosity is low in the Harash carbonate, reflecting the fine-grained nature and coalescence of the micrite matrix, regardless of intraskeletal pores that are occasionally large. However, higher levels of porosity (10-20%) were generated where rocks grade into wacke-packstones. Petrographic and petrophysical studies indicate that porosity in the Harash Formation is controlled by depositional environment and tectonic setting.***

1. Introduction

Upper Palaeocene-Lower Eocene deposition in the Sirt Basin in Libya has been the subject of considerable study in recent years (Bebout, D.G & Pendexter, 1975, Abdulsamad, E O, 1998) because of the importance of sediments of this age as hydrocarbon reservoirs. This paper, based on MSc. research (Elhamali, 1998), to investigate the sedimentology and depositional environments of the Upper Palaeocene-Lower Eocene Harash reservoir unit in the Sirt Basin, onshore north-east Libya. It includes facies analysis and interpretation of data from six exploration wells drilled by Sirte Oil Company within Concession 6 (Fig.1). The Harash Formation is found in the subsurface of much of the central and western Sirt Basin (Fig. 2). It reaches its thickest development in the Zallah Trough (~400ft / 122m) and thins to ~102ft /30m on the Az Zahrah-al Hufrah and Zaltan Platforms, ~204ft / 62m in the Maradah and Ajdabiya Troughs and ~102ft / 31m in the southeast Sirt Basin (Hallett, 2002) (Fig. 3). The Harash Formation is normally conformably overlain by the Kheir Formation but more rarely the Lower Eocene Gir Formation (Barr & Weegar, 1972). Core porosity of the Harash Formation ranges from >1 to 21% with an average of about ~10%. The most common porosity in the Harash Formation are inter-intragranular, vuggy, and mouldic types and these strongly influenced reservoir quality. Most of the good porosities (~20%) are observed in the upper part of the Harash Formation (wacke-packstone facies).

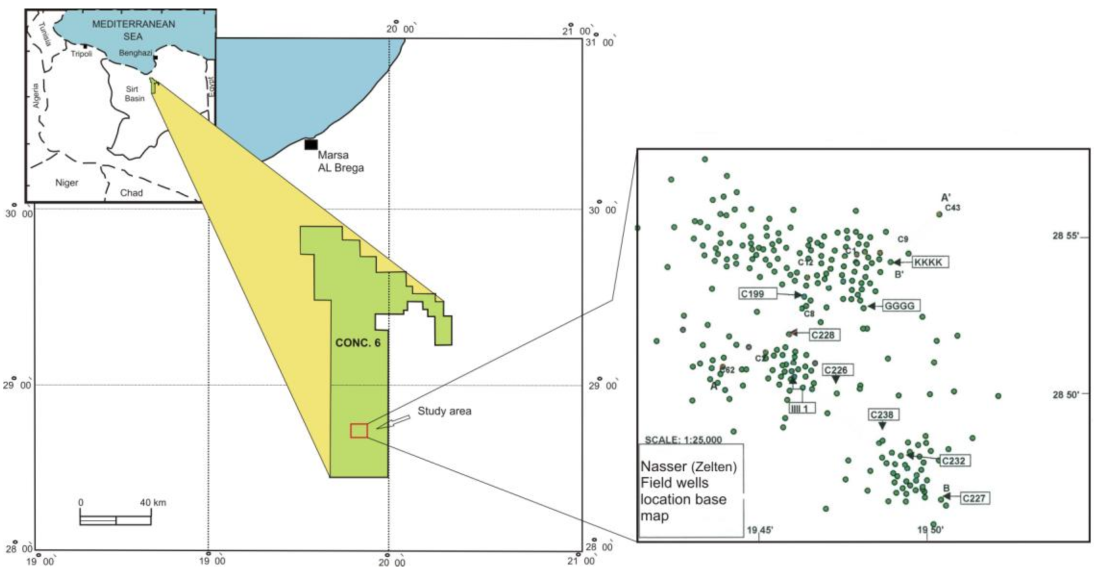

Figure 1: Location map and distribution of the wells in the Nasser (Zelten) field (study area): South Concession 6 in North Central of the Sirt Basin, Libya

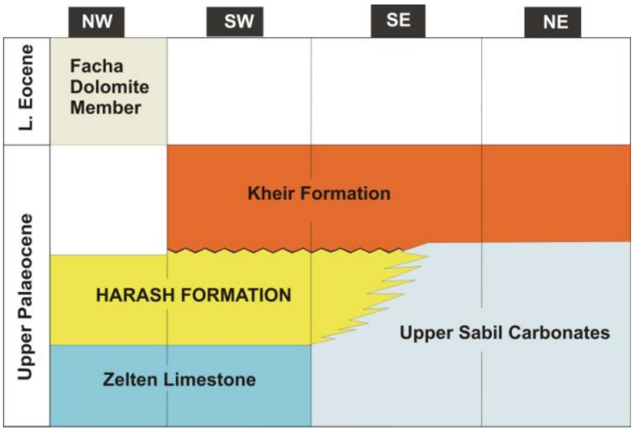

Figure 2: Generalized stratigraphic correlation chart of the Upper Palaeocene-Lower Eocene succession on the study area

2. Geological Setting

The Palaeocene section of the Eastern Sirt Basin consists of a carbonate succession which developed in response to subsidence and widespread marine transgression following Cenomanian rifting. The area of study in the Sirt Basin is located in concession six, approximately 160kms south of the Gulf of Sirte in the central portion of the Cretaceous-Tertiary Sirt Basin of Libya. The field was developed to form the giant Nasser (Zelten) oil field (Fig.1). The Sirt Basin was formed at the beginning of the Upper Cretaceous when extensional forces caused the break-up and collapse of the former Sirte Arch. It has been hypothesised that the continued elevation of the Sirte Arch caused the collapse of its crest (Calbic & Smith, 1967). A series of northwest trending horsts and grabens developed on the axis of the old Sirte Arch, gradually diminish in magnitude and disappear to the north and south (Fig. 3). This block faulting appears to have initiated the Cretaceous-Tertiary transgression in the Sirt Basin area. Thick shales (The Sirte Fm) and fine-grained limestones (The Kalash Fm) were deposited in the troughs. The Cretaceous deposits are thin on the platforms but include high hydrodynamic energy carbonate rocks and sandstones (The Waha Fm) as well as minor shales and carbonate mudstones. During the early Tertiary (Palaeocene), the Hagfa Shales with carbonate mudstone intercalations were deposited in deeper parts of the basin. These are overlain by the Khalifa shales and carbonates, which are thought to have been deposited in an open sea environment. Above these, a thick carbonate sequence, the Jebel Zelten Group (The Harash, and Zelten Formations), exhibiting various depositional and diagenetic facies of a reef complex, developed on the platform in conducive positions to reef accumulation. A partial regression during the lower Eocene created restricted conditions in which evaporites were deposited over the southwestern portions of the basin. The stratigraphic succession in the onshore Sirt Basin comprises granitic basement overlain by clastics, limestones, dolomites and evaporites ranging in age from Precambrian to Recent.

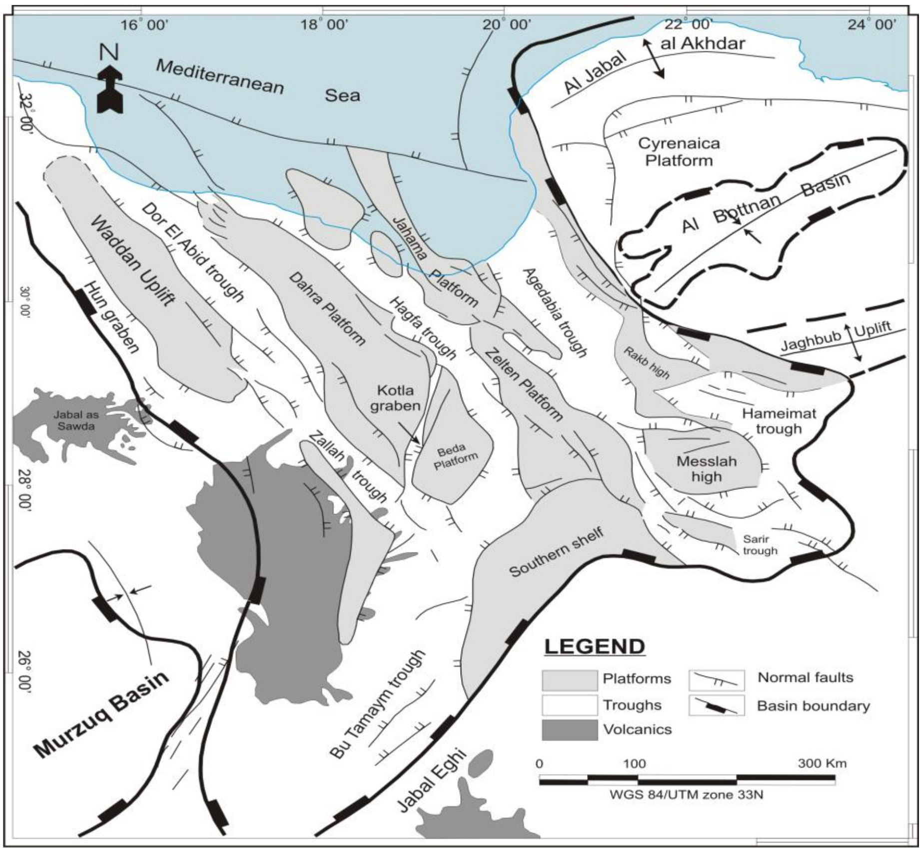

Figure 3: The tectonic framework of the Sirt Basin (modified after Mouzughi and Taleb, 1981)

3. Materials and Methods

This study is based on the investigation of core samples, thin-sections and wireline logs from six wells (C227, C228, C199, C238, IIII1 and KKKK1-6) from the Nasser (Zelten) oilfield (Fig.1). Laboratory studies included logging of approximately 180ft of cores using hand lens and binocular microscope. Approximately 87 polished and unpolished Thin-sections were stained with Alizarin Red S (Dickson, 1965) and potassium ferricyanide and studied using standard petrographic techniques. The terms employed to describe the crystallization fabrics follow Friedman (1965), and those for carbonate classification follow Dunham (1962). Some thin-sections were impregnated with blue-dyed resin in order to determine the relative porosity of the rock. Determination of the types of porosity follows the scheme established by Choquette and Pray (1970).

4. Lithofacies and Depositional Environments

The Upper Palaeocene-Lower Eocene subsurface strata of the study area can be classified into six separate sedimentary facies (summarized in table 1) based on sedimentological and petrological investigations of cores, thin-sections and well-logs. The main bioclastic components are larger benthic foraminifera, especially *Operculina*, *Discocyclina* and Nummulites, as well as planktonic foraminifera and other bioclasts. These facies were predominantly deposited under shallow-marine conditions, within the photic zone, as indicated from their richness in phototrophic fauna and flora, and can be interpreted as deposited in a carbonate ramp setting.

Table 1: Facies of the Harash Formation in the studied wells of the Nasser Field (Zelten)

Facies	Grain Types	Environment
Peloidal, molluscan, *Operculina*, wackestones (F1)	Peloidal, *Operculina*, Mollusc fragments, echinoderms, and ostracods	Inner-middle shelf, shallow marine environment
Operculina-miliolid, locally peloidal, dolomitic-mudstones (F2)	*Operculina*, miliolids, dolomite and pyrite	lagoonal
Peloidal, *Operculina*-miliolid, dolomitic-mud-wackestones (F3)	Peloidal , *Operculina* sp, miliolid	warm temperate shallow-water environment
Peloidal, *Operculina*-nummulitic, locally miliolid, mudstones (F4)	*Operculina*, miliolids, echinoderm and bivalve	shallow marine-lagoonal environment
Operculina-Discocyclina-rich, nummulitic, wacke-packstones (F5)	*Operculina*, *Discocyclina*,, Nummilites and Molluscan fragments	transitional zone between open marine and restricted environments
Peloidal, *Operculina*, nummulitic mud-wackestones, locally packstones (F6)	Peloidal, *Operculina* , Nummilites, miliolids, rotalids and *Discocyclina*	inner-shelf, shallow marine environment

4.1 Peloidal, molluscan, *Operculina* wackestones (F1)

This facies is represented in cores from wells KKKK1 in the northeast and C227 in the southeast of the Nasser (Zelten) Field. It is mainly composed of peloidal wackestones, grading into mudstones (Fig.4). Whole and fragmented *Operculina sp.* is the predominant foram (43-48% of the total foraminifera); the other common components are mollusc, bryozoans, ostracod fragments and echinoderm plates and spines.

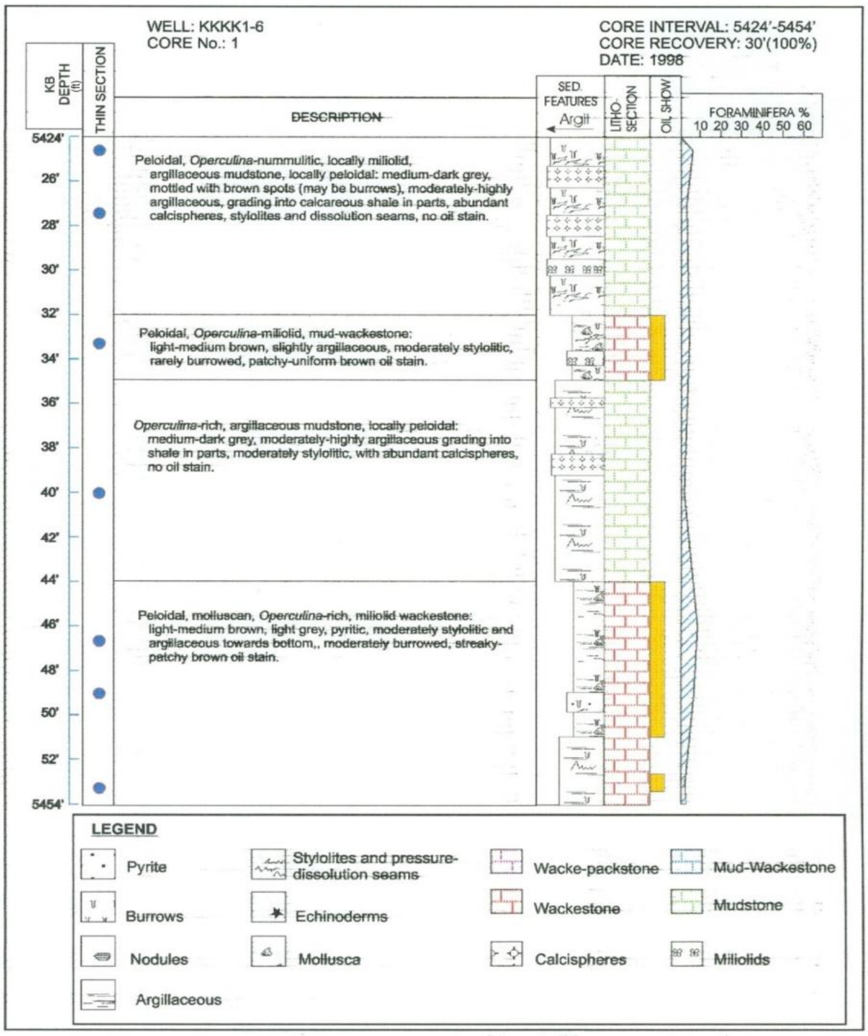

Figure 4: Generalized columnar section showing the different litho-and bio-faces, Harash Formation, well KKKK1-6

4.1.1 Facies interpretation

This facies was probably deposited on a wide, shallow that present in the whole area of the Nasser Field (Fig. 5). It is characterised by the domination of wackestones rich in *Operculina sp*. with few molluscs, echinoderms, and ostracods. However, the occurrence of coarse-grained molluscan fragments and the variety of the fauna implies an inner-shelf, shallow marine environment with open circulation (Murray, 1991; Drzewiecki and Simo, 1997). The presence of detrital grains in the matrix of this facies suggests a period of clastic influx and relative proximity to a source. All of these features lead to the interpretation that this wackestone facies (F1) was deposited in an inner-middle shelf, normal marine, shallow-water environment subject to open circulation.

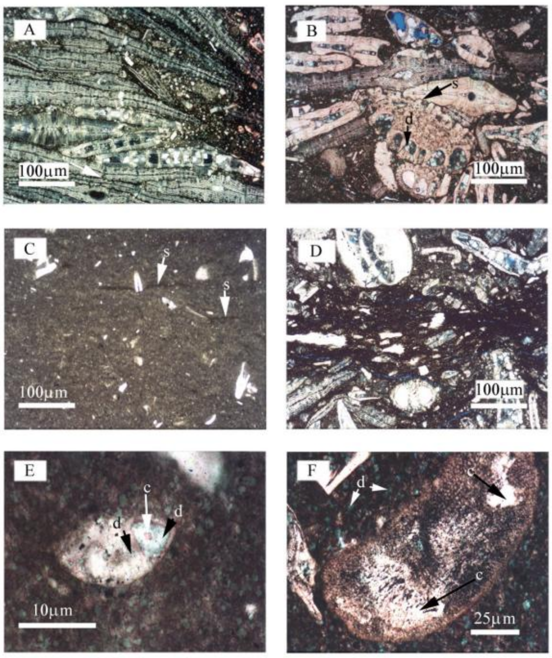

Figure 5: plane polarized photomicrographs. A) Fitted fabric in Discocyclina-Operculina-rich packstone from facies-F5. B) Fitted-fabric and-grain sutured seams (s) can also be observed in wackestones. Note calcite cement in foraminiferal chambers and occasional replacement by

dolomite. Intraskeletal porosity (deep blue areas) is also obvious in few forams

C) Represents an old dissolution seam (arrows) in clayey mudstone sample. The dolomite percentage is low. D) Non-porous stylolite swarm characterized by brown residues in wackstone sample and common intraskeletal porosity (blue-dyed areas). E) Calcite in an ostracod chamber has been replaced by dolomite. Note incised dolomite (black d) in the ostracod test and the presence of calcite rhomb (c) in the dolomotized area, suggesting some sort of calcitization process. F) Illustrates a partially neomorphosed echinoderm plate (light areas).

4.2 *Operculina*-miliolid, locally peloidal, dolomitic-mudstones (F2)

This facies is only recorded from wells C227-6 in the SE and KKKK1-6 in the NE of the Nasser Field. Units range in thickness from 3-10 feet and have a gray- medium gray colour. Poorly sorted, fragmented and whole robust, flattened *Discocyclina* comprise between 25-50% of this facies, and are associated with whole and fragmented miliolids and nummulites (<10%). Less common bioclasts are echinoid plates, bryozoa and small benthic foraminifera. The matrix is dominantly composed of finely fragmented bioclasts. Pellets are often difficult to distinguish from the micrite matrix, especially in dolomitized and/or neomorphic micrite. Pressure dissolution seams and micro-stylolites were the only structures seen in this facies. Poor-good visible porosity (5-13%) includes small vugs and intragranular pores. The permeability is low due to poor interconnections.

4.2.1 Facies interpretation

The first regression in the region is recorded in the deposition of Facies-F2, characterised by reduced grey subtidal deposits of argillaceous *Operculina-rich* mudstones. The relative scarcity of the biota, the dark colouring of the mudstones and the presence of highly argillaceous and clay materials, where carbonate mudstones grade into highly calcareous shales, are the common characteristics of this facies. Facies-F2 is absent or not cored in the southern region (wells IIII1-6, C228-6, and C199-6), so the lateral extension of the facies has been interpreted from log-correlation but it appears to have covered the whole area of the Zelten Field. In the northeast (well KKKK1-6), the occurrence of relatively high concentrations of dolomite (unstained carbonate) with minor amounts of framboidal pyrite suggests deposition in a reducing environment. Sulfate reduction may promote dolomite precipitation by simultaneously removing the sulfate ion as a potential inhibitor to dolomite precipitation (Baker and Kastner, 1981). However, these reducing conditions may only have been within pore waters, and not necessarily at the sediment surface. Calcispheres, which are only recorded in the core from well KKKK1-6, are possibly the reproductive cysts of dasycladacean algae and are lagoon indicators (Selley, 1985). Thus, considering all this evidence, the environment in which this facies was deposited was probably calm or with little agitation. The rarity of otherwise common shallow-water taxa, such as echinoderms, corals, bryozoans and red algae, suggests that while generally marine, this environment may have been separated from the open sea (Garea and Braithwaite, 1996) and essentially “lagoonal”. In the southeast (well C227-6), the *Operculina*-nummulites sp. association prevailed and is considered as evidence of a warm temperate shallow-water environment (Betzler, 1998).

4.3 Peloidal, *Operculina*-miliolid, dolomitic-mud-wackestones (F3)

Units range in thickness from 3-7 feet and have a light brown- gray colour, crypto-microcrystalline, slightly argillaceous, peloidal mudstone, grading into wackestone. The Facies contains <10% of benthonic foraminifera with abundant *Operculina* (48-54%), associated with <10% miliolids and nummilites. Less common bioclasts are echinoderm, brachiopod, ostracod and mollusc fragments. The unstained carbonates including dolomite represent only 3.7% of the total rock volume in well C227-6, but are abundant and widely dispersed forming 33.2% in KKKK1-6. Patchy inter- and intra-granular porosity (5-14%) revealed by the penetration of blue resin.

4.3.1 Facies interpretation

This facies relatively thin compared with the underlying Facies-F2, and this may suggest that the transgression was only brief so that carbonate production was too little and ineffectual. Facies-F3 has similar characteristics to Facies-F1, but in the northeastern portions of the Zelten Field (well KKKK1-6), a restricted environment is likely to have prevailed. This restriction allowed foraminiferal assemblages like *Operculina* sp. and miliolids to dominate. Barriers forming a lagoon may have caused the restricted environment. Such barriers may have been shelf-edge coral reefs, coastal irregularities of the inner-shelf, or have resulted from shallowing of the water by excessive shelf width, which restrains the water circulation (Scholle *et al*. 1983). In the southeast (well C227-6), *Operculina sp.* and nummulites are few in numbers, and are considered as evidence of a warm temperate shallow-water environment.

4.4 Peloidal, *Operculina*-nummulitic, locally miliolid, mudstones (F4)

Facies-F4 is similar in thickness across the area (5-9 ft). *Operculina* and miliolids are the dominant foraminifera species with maximum accumulations in the northeast. Large echinoderm and bivalve fragments (<4% of the rock volume) with rare fragments of gastropods, bryozoans and calcareous algae, associated. Intensive stylolitization and the presence of nodular structures, bioturbation and small-scale shale lumps distributed in the facies in all of the studied wells. This facies locally grades into marl and is also characterised by the presence of highly argillaceous seams formed in stylolites, which in places reduce porosity.

4.4.1 Facies interpretation

The final regressive phase is indicated by the deposition of the *Operculina*-nummulitic–locally (in the NE) miliolids argillaceous mudstones of Facies-F4. The distribution of the fauna reflects the environment under which this facies was deposited. This suggests some sort of restriction in the northeast (probably due to a high topographic relief or a barrier) and a more open area towards the south and the southeast. Facies-F4, in northeastern parts of the Nasser field represents a shallow marine-lagoonal environment. The presence of miliolids in the northern (well C199-6) and the northeastern parts of the Field (well KKKK1-6), and their absence in the southeast (well C227-6), suggests that the paleo-water depth was relatively great in that direction. Miliolids are common in open and restricted platforms and are rare in deeper settings (Abdulsamad, 1998).

4.5. *Operculina-Discocyclina*-rich, nummulitic, wacke-packstones (F5)

Facies-F5 is either absent or not cored in well KKKK1-6, but is well developed in other studied wells (C227-6, IIII1-6, C228-6 and C199-6). It is the thickest unit present in the studied section of the Harash Formation and represents alternating mudstone/wackestone-wackestone/packstone cycles (up to 30 ft). Porous intraclasts are locally present and horizontal and vertical burrows are abundant. The foraminifera *Operculina*, *Discocyclina*, and nummulites, form 10-43% of the total rock volume, and flourished in this facies. Other species like miliolids, rotalids, and *Orbitolina* are also present, but in small numbers. Molluscan fragments (<3% of the rock volume); a few echinoderm plates, and rare brachiopods, bryozoans and unidentified make up the remainder of the bioclasts. Calcispheres (tintinnines) are only abundant in the uppermost sections of the core in C199-6. The matrix comprises widely disseminated unstained carbonates including dolomite, and forms 10-60% of the rock volume. Dolomite also replaces bioclasts. Saddle dolomite, characterised by curved faces and sweeping extinction, is rarely recorded in the interval from wells IIII1-6 and C199-6. Porosity is also variable in well IIII1-6, which shows an alternation of porous and tight zones (8-10% porosity).

4.5.1. Facies interpretation

This facies reflects a marine transgression over a gently dipping shelf. Alternating small-scale cycles of mudstone/wackestone-wackestone/packstone are repeated several times in response to probable sea level fluctuations and/or tectonic movements. Generally, Facies-F5 is less argillaceous than Facies-F4, as it has low GR-values, and the burrows and lithoclasts recorded remained uncemented and porous (stained blue with resin), whereas transitional zones between dissolution seams appear to have been calcite-cemented. This is similar to the Oligo-Miocene outer ramp deposits from Sicily and Malta described by Wright and Burchette (1996), as deposits infrequently disturbed by storms. Calcispheres (tintinnines) are only abundant in the uppermost sections of well C199-6, and are lagoon environment indicators (Selley, 1985), although they are associated with other foraminifera such as *Discocyclina* sp., *Operculina* sp., miliolids, and nummulites. This may suggest deposition in a transitional zone between open marine and restricted environments. The occurrence of *Discocyclina* sp. in this facies may also corroborate the evidence of the paleo-water depth increasing, as they possess larger tests (Racey, 1998). A more open environment is thought to have persisted in the northern (well C199-6), southern (wells IIII1-6 and C228-6) and southeastern (well C227-6) parts of the Zelten Field.

4.6 Peloidal, *Operculina*, nummulitic, mud-wackestones, locally packstones (F6)

Facies-F6 is only recorded from the top sections of the cores from wells C227-6 & IIII1-6 (7-15 ft thick) and is absent or not cored in other wells. Light-medium-brown, cryptocrystalline, non-slightly argillaceous, peloidal, mud-wackestone, locally grading into packstone. *Operculina* and nummulites are the abundant species but are less common than in Facies-F5. Other species like miliolids, rotalids, *Discocyclina*, *Orbitolina* and *Planorbulina sp.* are also present but in a small numbers. Large molluscan shell fragments, bryozoans, echinoderms, brachiopods, and ostracods are also present (Table 1 and Fig. 5). The facies is highly bioturbated in well IIII1-6, and comprises flasery and nodular structures surrounded by stylolites. It is only slightly to moderately bioturbated in well C227-6. Pervasive pressure-dissolution seams are locally present. Detrital feldspar grains are recorded under CL in all of the studied samples.

Unstained carbonates, including replacive dolomite, are disseminated in the matrix and form 14% of the total rock volume in well IIII1-6 and 30-55% in well C227-6. A light brown oil stain is present in both wells and 20-30% of the total volume of the rock contains patchy inter- and intra-granular porous areas revealed by the penetration of blue resin. Log-calculated porosity reads as high as 12%, with water-saturation 20-50%.

4.6.1 Facies interpretation

This facies was deposited in southern (wells IIII1-6 and C228-6) and southeastern (well C227-6) parts of the Zelten Field as a result of an increase in paleo-water depth, but distribution was probably governed by a probable relatively high topographic relief present in the north (well C199-6) and the northeast (well KKKK1-6). Facies-F6, contains a fauna of Lower Eocene to Recent that indicates an inner-shelf, shallow (0-50m), temperate-warm marine environment (Murray, 1991). The GR-Curve for this facies is flattened and has low amplitude indicating a low rate of sedimentation. Facies-F6 represents the latest phase of deposition of the Harash Formation carbonates as it overlain by the Kheir sequence of Lower Eocene.

5. Discussion and Overall Depositional Interpretation

Aigner (1983) summarized that large foraminifera commonly occur in neritic and shelf-ramp environments in many parts of the Mediterranean Palaeogene successions and are considered to have formed as banks or reefal buid-ups. The Harash Formation is subdivided into six lithofacies that have been deposited in a low-energy marine environment below wave base. The wells located in the eastern portion of the study area are characterized by domination by miliolids, indictors of deposition in a restricted marine environment. In contrast, *Discocyclina* and nummulites are more common in the wells located in the western portion of the study area, and indicate deposition in a more open shallow-marine environment. Shallowing-upward sequences deposited on carbonate shelves and platforms have been studied by many workers (e.g. Laporte, 1967; Ginsburg, 1975; Wilson, 1975; Enos, 1983; Lindsay and Kendall, 1980). Although no evidence for shelf edge in the area of study can be established because of lack of data. It is likely that the lithofacies of the Harash Formation were controlled by changes in sea level, and were also influenced by tectonic movements. During periods of high sea level, carbonate production increases, because of the great extent of shallow shelf seas, and the biota tends also to increase because of the availability of oxygen and low temperature gradients. Conversely, in periods of low sea level, the sediment-supply increases and the faunal diversity decreases (Scoffin, 1987). No evaporites were recorded from the studied cores but evaporites were deposited in the Lower Eocene in the southwestern portions of the Sirte-basin (Keskin, 1988).

The final setting of the Harash Formation lithofacies is illustrated in Figure 6. This suggests that while a restricted to lagoonal environment is likely to have prevailed in the northeast (well KKKK1-6), a more open environment was present in northern (well C199-6), southern (wells IIII1-6 and C228-6) and southeastern (well C227-6) parts of the Nasser (Zelten) Field.

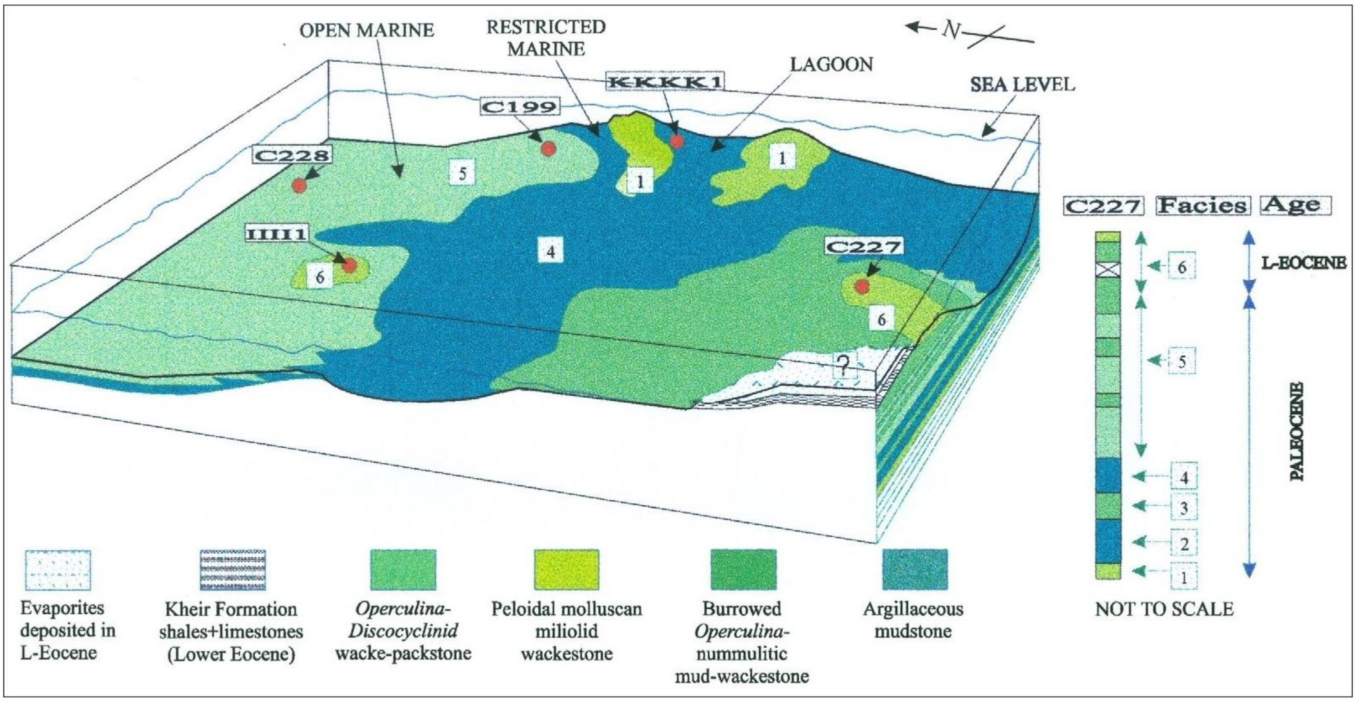

Figure 6: Depositional model of the Harash carbonate

6. Conclusions

The Upper Palaeocene Harash Formation has been studied in six wells in the Nasser field, Concession 6, Sirt Basin. Detailed core description and petrographic study show that the Harash Formation consists mainly of shallow-water carbonate and is characterized by facies and thickness variations between the six wells. The vertical and lateral variation of the Harash depositional facies was influenced by basin-floor architecture and other environmental control. Sedimentological and petrological investigation distinguished six lithofacies that have been deposited in a low-energy marine environment. The wells that are located in the east are characterized by domination by miliolids. These miliolids are indictors of deposition in a restricted marine environment, while *Discocyclina* and nummulites are more common in the wells located in the west, and indicate deposition in a more open shallow-marine environment. Petrographic and petrophysical studies indicate that porosities and permeabilities in the Harash carbonate are strongly related to the depositional environments. Porosity is at a maximum in the wacke-packstone facies and lowest in the lime mud facies.

7. Acknowledgements

This study was sponsored by the Libyan Government represented by the Higher Education Section and conducted at the Earth Science Department, University of Glasgow. The authers wish to express their thanks to both institutions for the provision of facilities; and Sirte Oil Company, Exploration Department, Libya, for providing data and permission to publish this paper. We also wish to thank the reviewers for their thorough and thoughtful reviews.

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