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The Role of Microfossils and Lithofacies on Groundwater Exploration (Al Jabal al Akhdar-Libya)

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Abstract: Twelve subsurface boreholes (water wells, maximum depth reaches 650m) have been stratigraphically studied and micropaleontologically investigated, which are located in an area extended from Battah to the vicinity of Darnah in the second escarpment of Al Jabal al Akhdar region, Northeast Libya. The microfossils (foraminifers and calcareous nannofossils) contributed directly in determining the age of the aquifers via in-situ diagnostic taxa and indirectly via stratigraphical position and lateral correlation in relation with the neighboring wells. The aquifers are varied in depth from well to well. Some are produced from the Cretaceous dolostones as in the wells located in the flange-like of the Cretaceous structural anticlines. The rest of the wells produce water from Eocene nummulitic limestones. Meanwhile, the Oligo-Miocene sections are not productive, which could be attributed to the work of the diagenetic processes (i.e. dolomitization, dissolution and fracturing) which enhanced the porosity and permeability. Occasionally, micritization and cementation deteriorated both of them. A stratigraphical correlation of the concerned wells is also generated to show the lateral variation in facies properties. The water analysis of the penetrated aquifers showed good to excellent water quality. The total dissolved salts (TDS) ranging between 400 ppm in the Cretaceous aquifers to 800 ppm in the Tertiary aquifers. The average yield rate of the water in the wells is 10 liters/second. This may be linked to the textural and petrographic characters of the aquifer.

Key words: Microfossils · *Nummulites* · Diagenesis · Biozone · Eocene · Libya

INTRODUCTION

Tertiary and Upper Cretaceous carbonate rocks are the main constitutes of the aquifers in Al Jabal al Akhdar area. While perched aquifers generally occur locally in Quaternary deposits, the karstification play important role in the presence of water bodies in the whole area. Groundwater flow is mainly related to a system of microfissures and micropores. The recharge of the aquifers is due to the direct infiltration of rainfall and to the seepage of runoff water along the wadies beds. This paper deals with the exploratory wells that drilled in the Al Jabal al Akhdar area, where, the Eocene and Upper Cretaceous aquifers has the high potential as water resources in term of quality and quantity and their spatial extension is mainly around the middle parts of Al Jabal Al Akhdar GWAE [1] (Fig. 1). The chemical quality of groundwater, expressed by the total dissolved solids (TDS), usually range from 450 ppm to 3000 ppm throughout Al Jabal al Akhdar area, whereas the quality decreases southward and eastward in relation to the leaching of evaporates, which occur in Tertiary deposits. In the northern coastal areas and as result of the increase in groundwater over-exploitation, groundwater quality decreases due to seawater intrusion. The same occurs in urban areas due to dominant pollution by septic tanks [2]. The groundwater is generally of sodium chloride type; however, for water of low TDS, the water is of a Calcium Bicarbonate type reflecting the nature of the Calcium Carbonate rocks of the aquifer. The ionic dominance is as follows in Arghain, [3].

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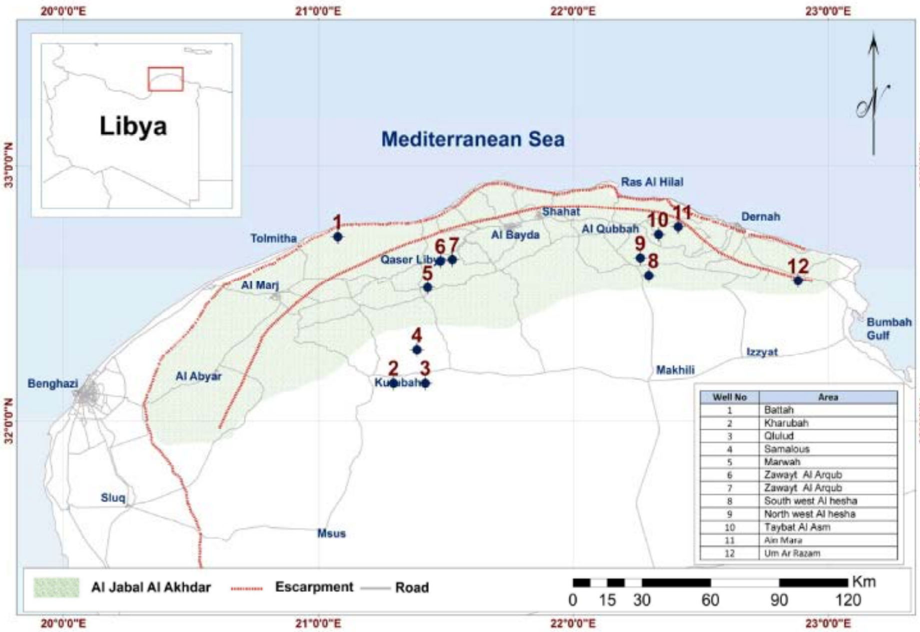


Fig. 1: Location map of the studied water wells in Al Jabal al Akhdar.

The water wells used in this study is almost distributed in different parts of Al Jabal Al Akhdar and their hydrogeological charac-teristics are variable in some wells. This paper aimed to describe the lithological facies and their micropaleontological contents with emphasis to the depositional paleoenvironment.

Location: Twelve water wells are drilled in the area bounded by latitude 32° to 33° N and longitudes 20° to 23° E (Fig. 1). Most of these wells are located on the second escarpment of Al Jabal al Akhdar, which is one of the structural elements of Cyrenaica.

MATERIAL AND METHODS

This work was based on samples from twelve water wells provided by General Water Authority (GWA) (Table 1) whom we are gratefully thankful. One hundred fifty-six selected cuttings samples were processed petrographically and micropaleontologically in order to reach the goals of this study. Dunham's classification of carbonate depositional textures [4], has been adopted herein, with Choquette and Pray [5] for porosity in this paper.

Thin sections are made of well consolidated rocks, or friable or poorly consolidated rocks. In order to facilitate recognition of porosity (blue powder dye) is added to the bonding cement (epoxy) to ease recognition of pore spaces which will be colored blue.

Table 1: Data base of this study.

Well no.	No. of samples	Studied interval (m)	Remarks
1	12	26-514	Tertiary Section
2	12	30-376	Tertiary Section
3	12	8-347	Indet. Section
4	12	9-324	Indet. Section
5	20	21-596	Tertiary – Cenomanian
6	21	8-650	Tertiary – L Cretaceous
7	12	55-601	Tertiary – L Cretaceous
8	12	82-547	Tertiary – L Cretaceous
9	10	12-479	Tertiary Section
10	12	24-569	Tertiary Section
11	11	22-388	Tertiary Section
12	10	20-196	Tertiary(Oligocene)Section

When necessary, Alizarin-red solution where used to differentiate calcite from dolomite. As samples are in the form of drill cuttings, therefore, each sample will contain more than one type of lithology and therefore, different corresponding paleoenvironment of deposition and diagenetic history may mislead. Some samples are described in more detail than others, based on the amount of information they provide.

Micropaleontologically, I) smear slides were prepared according to Bown and Young [6] in which, a small quantity of ditch cuttings sample is soaked in distilled water. A few drops of the solution were smeared onto a cover slide, using a flat toothpick

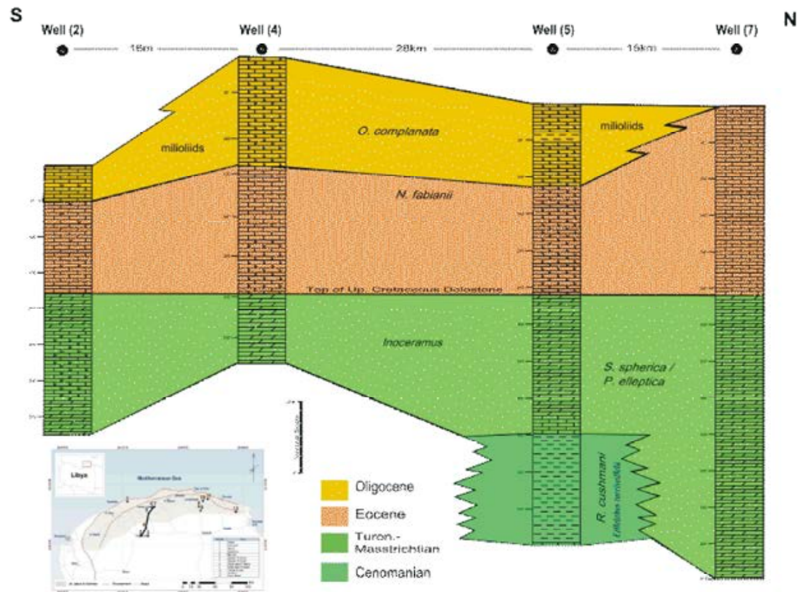


Fig. 2: North - South micropaleontological correlation of the studied wells.

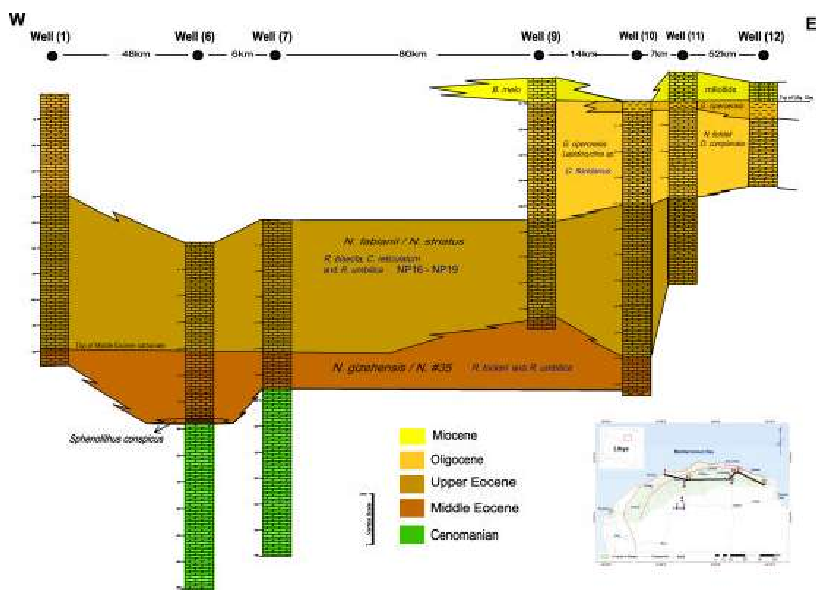
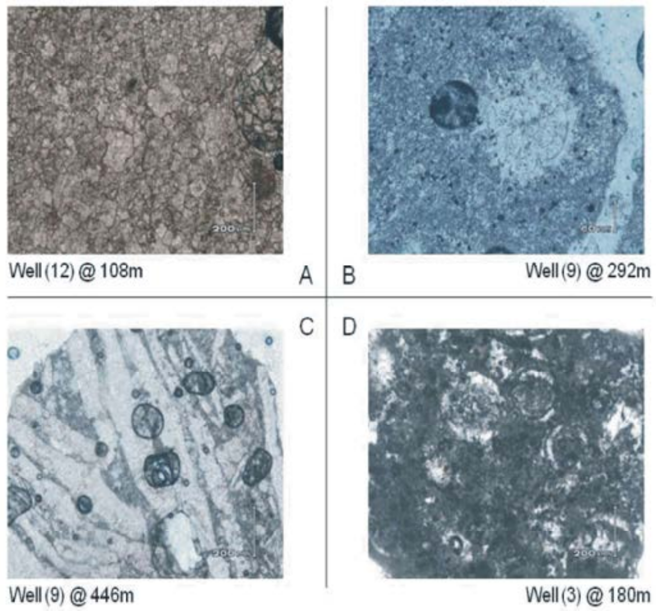


Fig. 3: East - West micropaleonyological correlation of the studied wells.

and then allowed to dry on hot plate and embedded on an objective slide with Norland optical adhesive which hardens after a few minutes under ultraviolet light. ii) Foraminifers are prepared according to standard micropaleontological techniques, in which samples are disaggregated by soaking in washing soda solution or Hydrogen peroxide solution in accordance to the sediment nature. This is followed by washing over a 63μm sieve to remove the silt and clay fractions. Samples are dried and picked.

Lithostratigraphy: This study is based on cuttings samples, therefore caving is the dominant problem which will mislead the corresponding ages, depositional environment and diagenetic histories. The Upper Cretaceous-Miocene sequences, represented by two cross sections (Figs. 2, 3), comprise nearly homogeneous carbonate nature limestone to dolostones with gradational variations (calcitic dolostones or dolomitic limestone), although clay intervals at some levels are of minor occurrence. The sequence comprises the following lithofacies (Plates I - III):

PLATE I (Texture)



EXPLANATION OF PLATE I

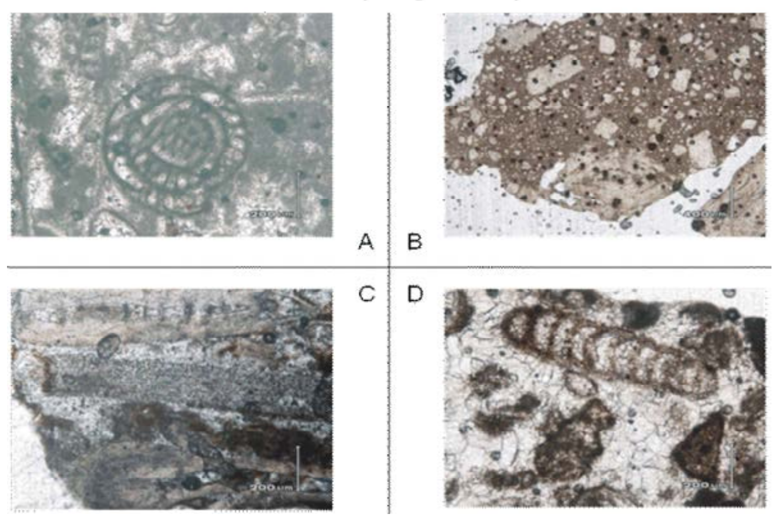
A: A view of Dolostone with common dolomicrospar matrix, with euhedral to subhedral dolomite crystals; (zoned in parts) Well (12) @ 108m depth; (PPL).

B: A mudstone texture with buliminid benthic foraminifera; WELL (9) @ 292m; (PPL).

C: A view of closely packed fragmented *Nummulites*; Well (9) @ 446m; (PPL).

D: A wackestone texture with partially leached miliolids; Well (3) @ 180m depth; (PPL).

PLATE II (Diagenesis)



EXPLANATION OF PLATE II

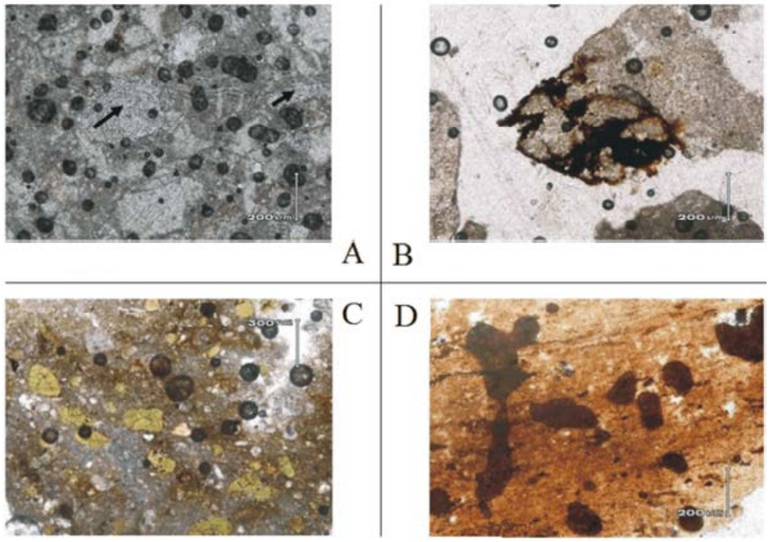
A: Close up view of deposited bioclast *Borelis* (center). WELL (9) @ 12m; (PPL).

B: Later stage Diagenesis of mechanical breakdown of microfossils (*Nummulites*); WELL (9) @ 479m; (PPL).

C: A view of echinoderm plate with syntaxial cement. Well (12); @ 34m; (PPL).

D: A view of grainstone texure shows *Rhapidionina* sp. and common blocky calcite cement; Well (4) @ 135m depth; (PPL).

PLATE III (Carbonate grains and accessary minerals)



EXPLANATION OF PLATE III

A: Authigenic grains of chert (arrows), WELL (9) @ 292m (PPL).

B: Another view of wackestone with common micrite matrix, with some iron oxides filled the fractures; Well (4) @ 231m depth; (PPL).

C: Accessory mineral: this texture contains a considerable amount of glauconite. Well (12); @ 34m; (PPL).

D: A view shows the characteristic appearance of Lignite. Well (2) @ 352m depth; (PPL).

Carbonate-dominated Lithofacies: Lagoonal to very shallow marine. It is partially preserved in the eastern wells (9, 11 and 12) which characterized by Limestone of white, hard, microcrystalline and yielded sparse microfossils of benthic foraminifers. This rock unit represents the youngest biozone in the penetrated successions probably correlates to Benghazi-equivalent "Al Jaghbuob" Formation (Fig. 3).

Clay–Carbonate Lithofacies: Shallow inner neritic-open marine. It is differentiated into two parts the uppermost thin layer corresponds to Al Faidiyah clay very correlatable to the exposed Umm Errazam clay. It is characterized by dark green, soft, slightly calcareous, slightly gypsiferous and glauconitic, it is partially preserved in the eastern wells (10, 11 and 12), while the lower packstone textured limestone is of light grey, hard, glauconitic and fossiliferous with mainly benthic foraminifers. This lithofacies correlates to Al Faidiyah Formation (Fig. 3).

Carbonate-Dominated Lithofacies: Inner neritic marine.

These carbonate-dominated deposits (Fig. 3) overlies dolostone and characterized by foraminiferal packstone – grainstone textured limestone grading to dolomitic limestone eastward (i.e. wells 9, 10). This lithofcies is largely of packstone textured limestone, which is composed of sparse micrite matrix, sparse foraminifers, rare echinoderm plates, sparse equant calcite, rare blocky calcite spar and rare syntaxial cement. It is grading to grainstone, wackestone or mudstone textured limestone in parts as in well (10). The upper part of this rock unit probably correlates to Shahhat Marl as suggested by Moody *et al*., [7] as well as El Mehaghag and Ashahomi [8], otherwise, Darnah Formation is well defined (Figs. 2, 3). On the other hand, at lower interval of Well (6) the Apollonia Formations is probably preserved (Fig. 3).

Dolostone-Dominated Lithofacies: Very shallow neritic marine-supratidal conditions.

These deposits are well developed (Figs. 2, 3) characterized by medium to coarse-crystalline in the lower part of the wells (3-7). This lithofacies is correlated with the Upper Cretaceous Wadi Dukhan Formation {as this dolostones is closely similar to that described by Muftah *et al*., [9] and/or Al Majahir-?Al Baniyah formations.

Marl–Dominated Lithofacies: Outer neritic marine environment of this marl deposits are well developed only in well (5) (Fig. 2) and characterized by yellowish, soft, slightly glauconitic and fossiliferous. This lithofacies is correlated with the Qasr al Abid Marl Formation.

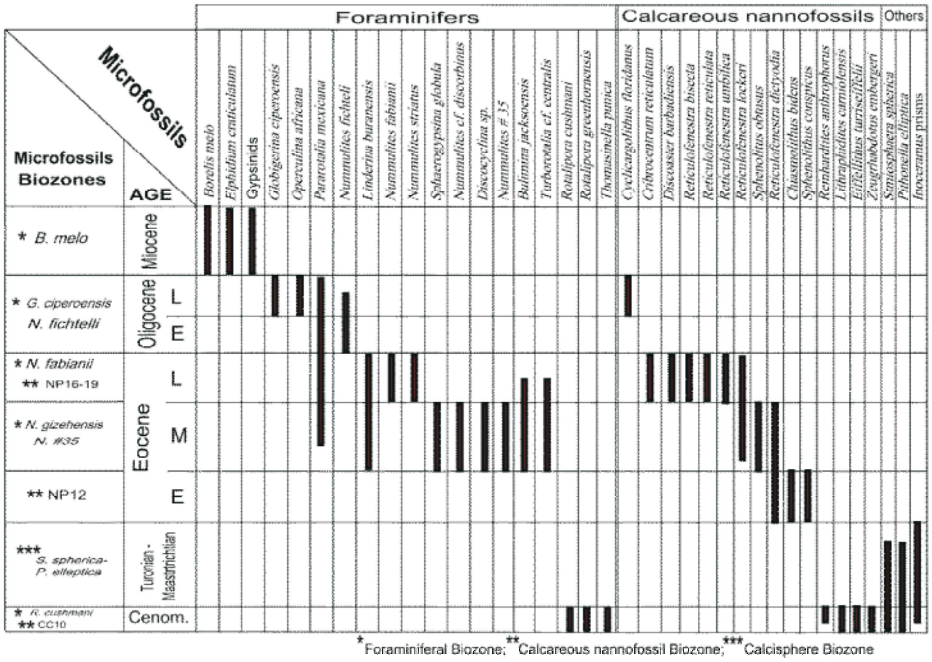


Fig. 4: Key microfossils of studied subsurface wells in Al Jabal al Akhdar region.

Biostratigraphical Analysis: The microfossils are the alternative to correlate the concerned wells spatially in order to understand the stratigraphical framework (Figs. 2-3). Although the penetrated successions subjected to extensive diagenesis at several levels and sometimes fossils are completely absent or mainly based on secondary zonal markers. An attempt is generated on the basis of microfossils (foraminifers and calcareous nannofossils) which are proved to be valuable tools in dating the subsurface sequences (Fig. 4), in particular the aquifer, the scope of this paper. Meanwhile at lower depths the stratigraphical position, lithology type and lateral correlation with known biozones are used instead as in the case of wells 6 and 7 (Fig. 3), where the lithology is dominated by dolostones and barren of microfossils.

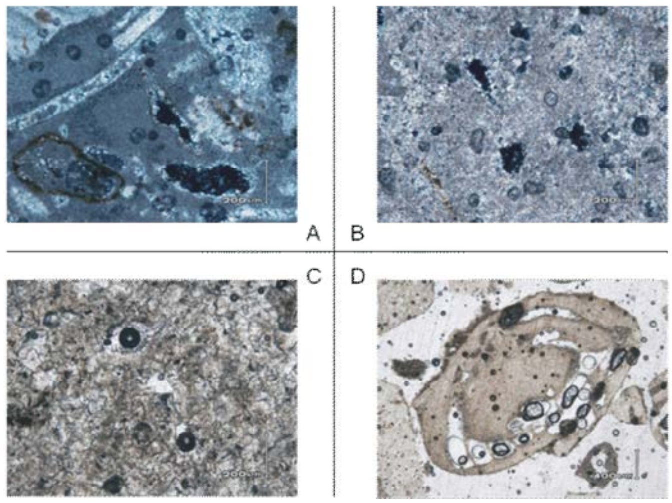
The Diagnostic Microfossils and the Biostratigraphical Correlations: Two biostratigraphical cross sections have been generated, the North – South correlation (the selected datum is the top of the Upper Cretaceous) (Fig. 4), where the brownish sucrosic dolostones with calcispheres from wells (2, 4, 5 and 7). The East – West Correlation has two data the younger datum is the top of the Oligocene which is represented by the base of the clay bed for the eastern four wells (9-12) and the second datum is represented by the top of the Middle Eocene carbonate for the western three wells (1, 6 and 7). The recognized biozones from both cross sections are from top to bottom as follows:

Borelis Melo Biozone (Middle-Late Miocene): It is recognized herein, by the First Down hole Appearance (FDA) of the diagnostic lagoonal-shallow benthic foraminifera *Borelis melo* in associated with *Cellanthus craticulatum* and *Gypsina* sp. as wells (9, 11 and 12) of East-West cross section (Fig. 3) (Plate V, fig. 7).

Oligocene Biozones: *Globigerina ciperoensis* Biozone of Bolli and Saunders [10] / *Nummulites fichtelli* Biozone of Racey [11] (Late Oligocene): The former biozone is confirmed by the FDA of *G. ciperoensis* in association with *G. praebulloides* as in wells (10-12) (Plate V, fig. 9). The latter biozone is confirmed by the *Nummulites fichteli* and the associated *Operculina complanata* and *Lepidocyclina* sp. (Plate V, figs. 2, 5) which are very indicative of this biozone at the Circum-Mediterranian area as evidenced in wells (4, 5, 11 and 12) (Figs. 2, 3). Similarly, the presence of the calcareous nannofossils *Cyclicargolithus floridanus* dated this unit as Late Oligocene as in the well (10) (Fig. 3).

Eocene Biozones: *Nummulites fabianii* Biozone of Racey [11] (Late Eocene): It is recognized herein, by the FDA of *N. fabianii* and the associated *N. striatus* with *Linderina buranensis* (Plate V, figs. 1, 3) for shallower facies as in wells (1, 6, 7, 10 and 11) and the *Bulimina jacksoensis* for the deeper facies as in well 9 (Figs. 3, 4).

PLATE IV (Porosity)



EXPLANATION OF PLATE IV

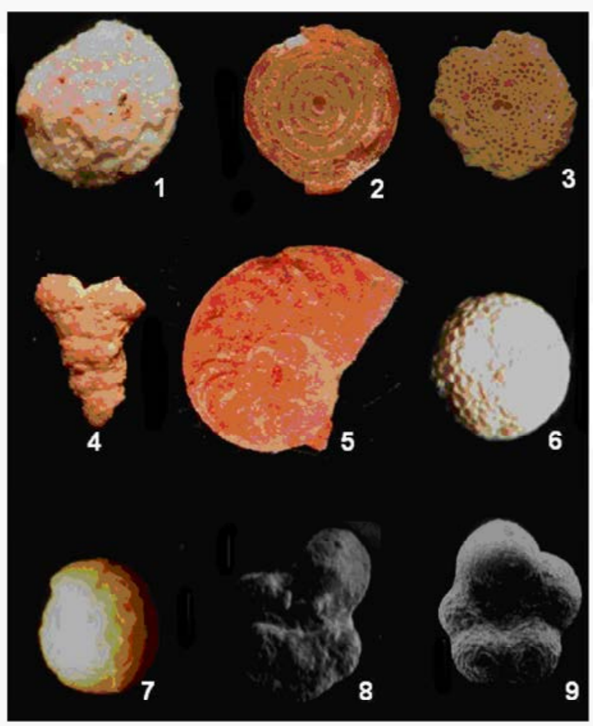
A: Shows example of intraskeletal porosity (black); Well (9) @ 77m; (XPL).

B: A view of mudstone with common dolomicrospar and sparse micrite matrix; note high porosity (vuggy dominated); Well (3) @ 154m depth; (XPL).

C: Intercrystallina porosity within a dolostone texture (in white). WELL (12); @ 108m; (PPL).

D: Shows intraskeletal within *Nummulites* porosity (White) WELL (9) @ 446m; (PPL).

PLATE V



1. *N. fabianii*; 2. *N. fichteli*; 3. *L. buranensis*; 4. *T. punica*; 5. *O. complanata*; 6. *S. globula*; 7. *B. melo*; 8. *R. cushmani*; and 9. *G. ciperoensis ciperoensis*.

(All pictures with bar scale = 1mm; except SEM photos 8,9 =100μm)

On the other hand, the presence of the calcareous nannofossils *Reticulofenestra bisecta*, *Cribrocentrum reticulatum* and *Reticulofenestra umbilica* are indicating NP16-NP19 biozones of Martini [12] as in the well (8).

Nummulites gizehensis-N. #35 and N. discorbinus Biozone (Middle Eocene): It is recognized herein, by the FDA of *Nummulites gizehensis, N. #35* (AGOCO's type collections) in association with *N. discorbinus, Sphaeorhypsina globula* (Plate V, fig. 6) and *Discocyclina sp.* as in wells (6, 9 and 10) (Figs. 3-4), whereas in the deeper settings such as in Well (1) *Turborotalia sp.* and *Bulimina jacksoensis* are used locally (Figs. 3 and 4). On the other hand, the calcareous nannofossils *Reticulofenestra lockeri* and *R. umbilicata* are also indicative (Figs. 3 and 4).

Reticulofenestra dictyodia–Neochiastozygus rosenkrantzii (NP11-12) (Early Eocene): These calcareous nannofossils Biozones of Martini [12] are recognized herein, by the FDA of *Reticulofenestra dictyodia* and *Neochiastozygus rosenkrantzii* and the associated taxa such as *R. minuta* as in well (6) and *Sphenolithus conspicus* which defines NP12 biozone of Martini [12] as in well (1). This rock unit probably correlates to Apollonia Formation.

Cretaceous Biozones*:* *Stomiosphaera spherica-Pithonella elliptica* Biozone (Turonian-Maastrichtian?): This calcisphere biozone is defined by the FDA of both zonal markers (*Stomiosphaera* and *Pithonella*) of Castro and Martinez-Gallego [13] as in Wells (5 and 8) and laterally traced by the stratigraphical position. The presence of *inoceramus* prisms is also useful (Fig. 2). Meanwhile in the East-West cross section the Cretaceous biozones are not recognized, which may be attributed to extreme dolomitization and shallower–supratidal depositional settings. These rock units are difficult to correlate due to the lack of foraminifers and calcareous nannofossils, although calcispheres and inoceramus assign wide range of correlation, in the range from Al Baniyah? - Wadi Dukhan formations.

Rotalipora cushmani **Biozne (Cenomanian):** This zone is introduced by Caron [14] and defined herein, by the FDA of *Rotalipora cushmani* and *R. greenhornensis* (Plate V, figs. 8, 9). The presence of the characteristic agglutinated foraminifera *Thomasinella punica* is very diagnostic according to Weidich and Al-Harithi [15] (Plate V, fig. 4). On the other hand, the occurrence of the diagnostic calcareous nanno-fossils *Zeugrhabdotus embergeri, Eiffelithus turriseiffelii*, *Watzn-aueria barnesae, Rhagodiscus aspersa, Arkhanglskiella confusa* and *Eprolithus floralis* are also indicative as in well (5). This Cenomanian rock unit is only reached in well (5) and correlates with Qasr Al Abid Formation (Figs. 2-4).

Diagenesis: Shallow water sediments often exhibit more complex diagenetic history than deeper water sediments as the former are composed of grains of different sizes and unstable minerals. All different aspects of diagenesis affecting the penetrated carbonates sequence in the studied borehole are listed in Figure 5 (Plate II) and discussed below:

Bioclast deposition: It is a direct deposition of the skeletal remains of fauna and flora as an early diagenetic stage. Apparently this deposition did not take place in wells (3 and 8) which may be attributed to the depositional environment or the dolo-mitization or both of them.

Lime-Mud Precipitation: It occurs as a direct precipitation of lime mud (Micrite) especially in Low energy environments. This preci-pitation dominates all studied wells, meanwhile it did not affect wells (3, 4, 5 and 8) which may be attributed to different environmental settings.

Micritization: It is a replacement process in which the carbonate component is gradually transformed to fine micro-crystalline calcite or micrite. This replacement process may involve all or part of the skeletal grain. Often micrite envelopes are the remnants of this process. As a result of this replacement the taxonomic affinities of the grains become obscured and described as peloids, which is defined as rounded, micritized or micritic carbonate grains of uncertain origins without internal structure. This case can be recognized in all other wells than (3, 5, 8 and 9) due to different diagenetic processes.

Fragmentation: Herein, represents an early stage in bioclasts deposition where currents or other environmental factors cause the breakdown of carbonate grains into smaller sizes. This process can be recognized in wells (4, 5, 6, 7, 10 and 12).

Microfracturing: This post-depositional feature is recognized only at the lowermost depths of well (1) in response to the extreme compaction.

Dolomitization: Limestone changed to dolostone, when dolomite crystals replace calcite crystals in process called dolomitization. This processes obliterated partly or completely the pre-existing microfossils. Therefore, these dolomitized sections are difficult to date. This middle to late stage diagenetic process dominates all wells.

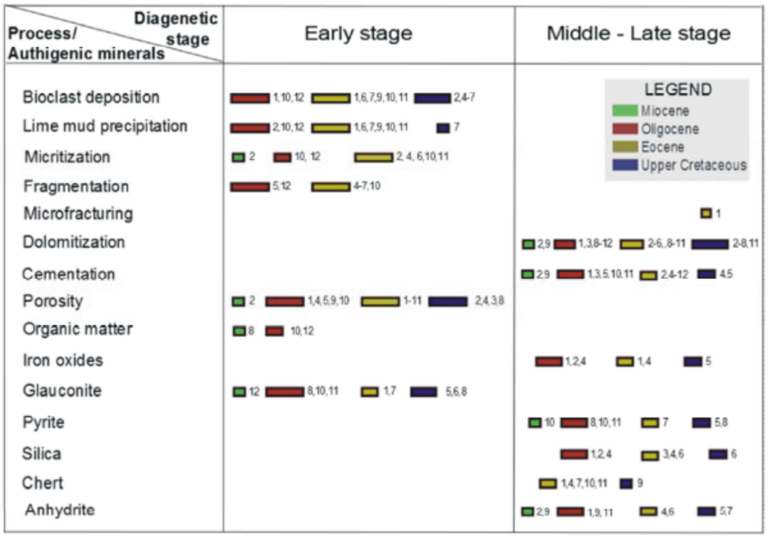


Fig. 5: Diagenesis affected the studied samples at different lithostratigraphical units in the studied wells. (Note: numbers against each bar refer to well number; bar length are arbitrary).

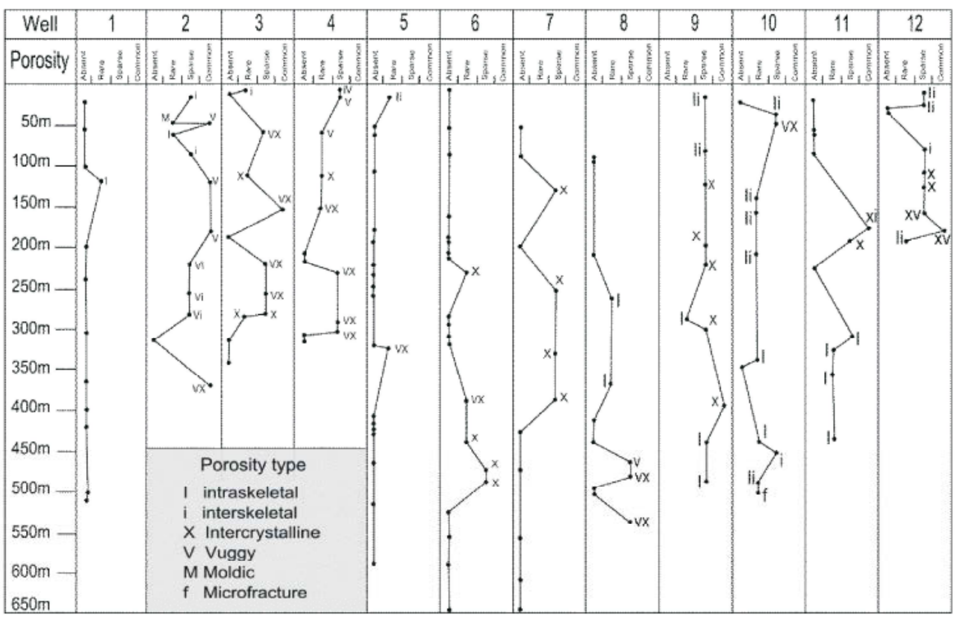


Fig. 6: Petrographical estimated porosity as obtained from cuttings samples from the studied wells.

Cementation: Cements of various mineralogies reduce the primary and secondary porosity in the studied intervals. Thus, the emplacement of the cement decreases total porosity and reduces the potential of aquifer quality. Calcite and dolomites are the dominant cements in most studied samples. This middle to late stage diagenetic process dominates all wells.

Dissolution: It represents the pore spaces formed at early stages (primary porosity) or late stages (Secondary porosity). It can be enhanced or destroyed by different diagenetic processes such as dolomitization and others. It is generally present by different amounts in the studied wells, meanwhile it is nearly absent in the wells (1 and 5) either because it is originally does not exist or it is in a form of micropores which are beyond the recognition power of the microscope.

Organic Matter: Generally organic matter can be trapped during sedimentation process and recognized in wells (8, 10 and 12).

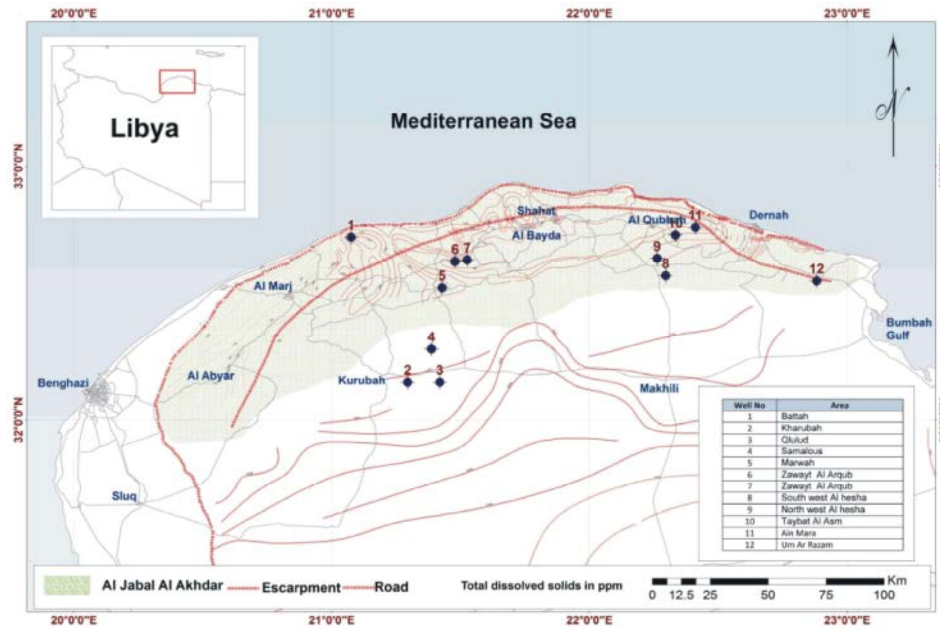


Fig. 7: Water quality map of groundwater of Al Jabal Al Akhdar modified after (Arghain and Hamad, 2006).

Iron Oxides: These oxides are formed as a result of oxidation processes and have been detected as stains in wells (1, 2, 4 and 5).

Glauconite: It occurs as disseminated grains in limestone. It is apparently formed under conditions of slow sedimentation in marine environments. It is reported in all other wells except the following wells (2, 3, 4 and 9).

Pyrite: It occurs as authogenic iron sulphide, precipitates readily in organic rich, reduced environments with sluggish circulation of pore fluids. Generally, pyrite occurs as scattered frameboids within the muddy micritic matrix or within the chambers of foraminifera, both environments favorable to pyrite formation. Pyrite is much less apparent in the platform facies which are well oxygenated sediments. It is recognized in the following wells (5, 7, 8, 10 and 11).

Silica: These terrigenous grains present as scattered grains in the following wells (1-4 and 6).

Chert: It is formed when supersaturated fluids percolates the pre-existed sediments and replaces the carbonate constituents. It is recognized in wells (1, 4, 7, 9-11).

Anhydrite: It is formed as a result of burial or compaction to covert this mineral from hydrous to anhydrous state by losing water. This mineral dominates all well with the exception of (3, 8, 10 and 12).

Porosity: Porosity is best developed in the platform sediments, where there are rare debris flows and limestones usually fractured. It can be of various types such as, intercrystalline, intraskeletal, moldic, fracture, intergranular and vuggy. Microporous systems are notoriously impermeable, a characterisitic which is attributable to small pore throat diameters. Microporous carbonate aquifer is fine grained sediments such as some lime muds, which are deposited with a high primary porosity. Post-deposititional compaction and cementation usually reduce porosity to virtually nil.

Porosity in the study area is featured by six types, four of them are dominant which are inter-intraskeletal, vuggy and intercrystalline (Plate IV), the other two types are of minor scale which are moldic and microfracture (Fig. 6). The best porosity types where developed in wells (2, 3, 4, 9 and 12) which may be enhanced by dolomitization. This implies that probably the porosity is best developed in southwest and northeast wells of the study area and it is generally of two types vuggy and intercrystalline. The other two skeletal types also considered and encountered in limestones and partly or selectively dolomitized limestone.

Rare presence of moldic and microfractured porosity are also encountered. Generally the worst porosities encountered in wells (1 and 5) which may be attributed to cementation or lack of primary porosity. This does not exclude the possible presence of micropores which could not be ruled out because this type is beyond the resolution of the used microscopes. Studied boreholes in general, show a general increase of porosity upwards in wells (2, 3, 4 and 9) while decreasing in wells (1, 5, 6 and 8) (Fig. 6). In other words we need more sophisticated tools like SEM and XRD which both were not (in hand) or available during the course of this study.

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