Microfacies and Depositional Environments Analyses of the Hartha Formation at Balad Oil Field, Central Iraq

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Abstract
The Hartha Formation (Late Campanian-Maastrichtian) has been recognized as a potential reservoir for hydrocarbons in various oilfields within the Mesopotamian basin in central Iraq. The formation has conformable upper contact with the overlying Shiranish Formation but unconformable lower contact with the underlying Mushorah Formation. This formation has been stratigraphically divided into two main parts. The lower part is particularly significant as it is recognized as an important stratigraphic unit due to the presence of oil shows. Five subsurface sections and many thin sections of the Hartha Formation (Late Campanian-Maastrichtian) were studied to unravel the depositional facies and environments. The sedimentary microfacies of the Hartha Formation in the Balad oil field include mudstone, wackestone, wackestone to packstone, packstone to Grainstone, and Rudstone. These depositional microfacies have been subdivided according to their primary and diagenetic constituents into six sub-microfacies. The microfacies have been deposited in deep shelf margin, open shelf, and foreslope of varying salinities and energy levels. Cementation, dolomitization, compaction and pressure solution (stylolitization), and dissolution are observed affecting variably both ground mass and particles. These diagenetic processes have both positive and negative effects on porosity types, causing fluctuations in porosity levels. The primary pore types identified within the study wells include interparticle porosity, intercrystal porosity, moldic porosity, vuggy porosity, channel porosity, and fracture porosity.

Keywords: Hartha Formation; Microfacies analysis; Depositional environment; Diagenetic process; Balad oilfield

1. Introduction

Hartha Formation represents one of the most important upper Cretaceous carbonate successions in central Iraq. It was formed during the Late Campanian-Maastrichtian Sequence (Jassim and Goff, 2006). This sequence includes the deposition of the Hartha Formation in south and central Iraq, which occurred due to a significant rise in sea levels (transgression). The sequence concluded with a stage of tectonic uplifting and subsequent fall in sea levels (Ahmed and Al-Zaidy, 2023; Aziz et al., 2024). Several studies have been conducted on the Hartha Formation. Al-Barzanjy (2020) identified four dominant microfacies types in the rocks of the Hartha Formation, including lime mudstone, lime wackestone, green algae lime
wackestone to packstone, and packstone microfacies. Al-Sammarai (2010) divided the Hartha Formation at the Balad oil field into two main paleoenvironments; a restricted marine shelf and a lagoons environment. Al-Naemi (2012) concluded that the Balad oil field has experienced two major faults (F1 and F2) and numerous minor faults (MF1, MF2 and MF3) (Fig. 2). These faults have a significant impact on the sedimentary basins of the Hartha Formation.

The Balad oil field was chosen to unravel the microfacies and depositional environments of the Hartha Formation. It is located in Salah Al-Deen governorate, approximately 9 km from Balad city and 60-70 km to the north of Baghdad governorate. It extends to the western bank of the Tigris River between Samara field in the north and east Baghdad field in the south (Fig. 1). This research aims to study the microfacies and the depositional environment of five boreholes in the Balad oil field, (Ba-1, Ba-5, Ba-6, Ba-7, and Ba-8) and investigate the diagenetic processes (Fig. 1).

2. Stratigraphy and Geological Setting

The Hartha Formation was deposited during the Upper Campanian- Lower Maastrichtian sequence in a carbonate inner shelf and lagoonal back reef environments surrounding the stable shelf margins. The stable shelf has been modified to include the Mesopotamian Zone, where the Balad oil field is located within the Tigris subzone (Jassim and Goff, 2006). This subzone is characterized by wide-ranging synclines and narrow anticline folds trending mainly NW-SE and E-W, accompanied by longitudinal normal faults (Fig. 2).

According to mud logging reports provided by North Oil Company (NOC, 1984), the Hartha Formation at the Balad oil field consists mainly of two parts: the upper part consists of limestone, chalky limestone, marly in parts, pyritic, dolomitic, argillaceous in parts, and fossiliferous. While, the lower part consists of limestone, fine crystalline, pyritic, porous impregnated with heavy oil, slightly argillaceous (shaly) in parts, pyritic, stylolites, and locally dolomitized. The lower part, which contains
the commercial oil, can be further divided into two units (A and B) based on well logs and petrophysical properties (Fig. 3).

![Fig 2](image)

**Fig 2.** The structural contour map at the tops of the Hartha Formation with the location of the studied wells

The upper contact of the Hartha Formation is conformable with the overlying pelagic sediments of the Shiranish Formation, while the lower contact is unconformable with the Mushorah Formation (Haq and Vail, 1987; Jassim and Goff, 2006). In the study area, the thickness of the Hartha Formation varies due to the presence of faults, resulting in different thicknesses at different locations: 444m in well Ba_1, 292m in well Ba-5, 292.5m in well Ba-6, 293.5m in well Ba-7, and 423m in well Ba-8.

3. Materials and Methods

Five subsurface sections were selected from the wells of the Balad oil field, including Ba-1, Ba-5, Ba-6, Ba-7, and Ba-8 to determine and reconstruct the depositional environment of the Hartha Formation (Fig. 1). For this purpose, 350 thin sections have been prepared from the core and cutting samples for five selected wells, including, 55 thin sections were selected from core samples obtained from wells Ba-1 and Ba-8, while 295 thin sections were obtained from cutting samples of the studied wells. The microfacies of the Hartha Formation were determined according to the types of grains (skeletal, nonskeletal), matrix, and cement materials. For this purpose, all thin sections were petrographically examined using a polarizing microscope at the Laboratory of the North Oil Company. The identified facies are classified according to Dunham's (1962) classification and compared with the standard microfacies analysis (SMF) of Wilson (1975). Machine work by Petrel software (version 2021) was
applied to digitize, modify, and generate the seismic control map at the top of the Hartha Formation and also to correlate between wells at the Balad oil field. It is important to note that the well-log data received from the North Oil Company only covers the lower part of the Hartha Formation.

4. Results and Discussion

4.1. Microfacies Analysis

Six main microfacies were determined within the Hartha Formation at Balad oil fields, including mudstone, wackestone, wackestone to packstone, packstone, Packstone to Grainstone, and Rudstone. Each type consists of sub-microfacies and is discussed as follows:

4.1.1. Mudstone microfacies

Most of the mudstone microfacies are composed of 90% micrite with only a small amount, less than 10% of skeletal grains including various species of planktonic Foraminifera such as globigerinoides and golobotruncana (Plate 1A).

Additionally, there is a small amount of echinoderm, bioclast, and calcispheres. This microfacies were identified in all the studied wells at different depths, especially at the upper part of the Hartha Formation. This microfacies correspond to Wilson (SMF-3) of FZ-3, that deposited in a deep shelf margin environment. This environment is characterized by its quiet depositional condition resulting from limited water movement and relatively high salinity.

4.1.2. Wackestone microfacies

Diversified assemblages of benthonic foraminifera together with echinodermal plates, and molluscan shell fragments are the main skeletal components of this microfacies. Depending on these components, the following sub-microfacies have been recognized:
Bioclastic Wackestone Sub-microfacies

Plate 1. Photomicrographs of microfacies in Hartha Formation. (A) Globigerinoides Sp in mudstone microfacies in well Ba-1 at depth 1758m, X100. (B) Bioclastic wackestone sub-microfacies in well Ba-1 at depth 1910m, X40. (C) Foraminiferal wackestone sub-microfacies in well Ba-1 at depth 1923m, X40. (D) Bioclastic wackestone to packstone sub-microfacies in well Ba-1 at depth 1758, X40. (E) Foraminiferal wackestone to packstone sub-microfacies in wells Ba-8 at depth 1924m, X100. (F) Echinoderms packstone sub-microfacies in well Ba-8 at depth 1659, X40. (G) Foraminiferal packstone sub-microfacies in well Ba-5 at depth 1907, X40. (H) Packstone to grainstone microfacies in well Ba-7 at depth 1716m, X40. (I) Rudist shells, rudstone microfacies in well Ba-5 at depth 2003m, X40.

It consists of skeletal fragments, and the dominant allochems are bioclast, echinoderm debris, molluscan shell fragments, calcispheres with different types of benthic foraminifera such as Rotalia and Orbitoides (Plate 1B). These grains are embedded in micritic or cryptocrystalline groundmass,
indicating a low to moderate-energy environment. Except for well Ba-5, the bioclastic wackestone sub-microfacies have been diagnostic in all the studied wells. This sub-microfacies is equivalent to Wilson (SMF-9) of FZ-7, which indicates an open shelf environment.

a) **Foraminiferal Wackestone Sub-microfacies**

It is characterized by a prevalence of benthic foraminifera, especially Rotalia and Orbitoides (Plate 1C). These skeletal grains make up more than 25% of the rock components, which are embedded within micritic groundmass, inducing a low to moderate-energy environment. The foraminiferal wackestone sub-microfacies are the most common and are found at different depths within all the studied wells. This sub-microfacies correspond to Wilson (SMF-8) of FZ-7, which indicates an open shelf environment.

4.1.4. **Packstone microfacies**

It represents one of the most common microfacies in the Hartha Formation. Benthic foraminifera (such as Rotalia and Orbitoides), calcareous algae, some calcispheres, and pyrite minerals, were the main constituents that occur in this microfacies. It can be subdivided into two sub-microfacies as follows:

a) **Echinoderms Packstone Sub-microfacies**

The primary composition of this sub-microfacies consists of echinoderms of various sizes, accompanied by other organisms such as bioclasts, Orbitoides, Monolepidorbis, ostracodes, bryozoans, and Rotalia. Echinoderms make up approximately 60% of the rock constituents and are embedded within a dark-colored microcrystalline groundmass (Plate 1F). This sub-microfacies was consistently observed at different depths in wells Ba-6, Ba-7, and Ba-8, which indicates a moderate to high energy environment. The echinoderms packstone sub-microfacies correspond to Wilson’s (SMF-10) of FZ-7, and it represents an open-shelf environment.

b) **Foraminiferal Packstone Sub-microfacies**

An abundant assemblage of benthic foraminifera such as Rotalia and Orbitoides with red algal fragments, echinoderms, and bioclast are the main constituents of this sub-microfacies (Plate 1G). This sub-microfacies was observed at different depths in all the studied wells that reflect moderate to high
energy environments. The foraminiferal packstone submicrofacies correspond to Wilson’s (SMF-8) of FZ-7, and it represents an open shelf environment.

4.1.5. Packstone to grainstone microfacies

This type of microfacies is characterized by a significant abundance of skeletal grains in terms of quantity and size, approximately more than 60% of the grains, and a smaller amount of micritic groundmass (Plate 1H). The skeletal grains in these microfacies consist of an assembly of benthonic foraminifera such as Rotalia and Orbitoides, along with some echinoderms. The packstone to grainstone microfacies were recognized in the upper part of the Hartha Formation at wells Ba-7 and Ba-8, which indicate high-energy environments. This microface corresponds to Wilson’s (SMF-5) of FZ-4, and it represents a foreslope environment.

4.1.6. Rudstone microfacies

This type of microfacies is composed of coarse-grained bioclasts (skeletal fragments) surrounded by a matrix or fine-grained carbonate mud. These fragments are not organically bound together and are mostly greater than 2mm in diameter (Al-Awwad and Pomar, 2015). Most of the skeletal fragments that have been recognized in this microfacies include rudist shells, Rotalia, Orbitoides, echinoderms, and shell fragments (Plate 1I). Rudstone microfacies are commonly found in shallow marine depositional environments, including reef environments and areas with strong currents and wave activity (Wright, 1992). This microfacies is found at different depths within the upper part of the Hartha Formation in well Ba-1 and at the lower part of well Ba-5. It corresponds to Wilson's (SMF-6) of FZ-4 within the foreslope environment.

4.2. Diagenetic Processes

Carbonates of the Hartha Formation have been affected by both early- and late-stage diagenesis and they have destructive and constructive effects on the reservoir characteristics. The main diagenetic process features observed in the Hartha Formation, include recrystallization, cementation, compaction and pressure solution (Stylolitization), dolomitization, and dissolution.

4.2.1. Destructive diagenetic processes

a) Recrystallization

Recrystallization is considered an early-stage diagenetic process in which the size of the crystals can increase or decrease without any chemical alterations (Folk, 1965). The recrystallization commonly affects both the micritic matrix and the skeletal grains of the Hartha Formation causing partial or complete recrystallization of the micrite to miccospar. This recrystallization process has been observed at different depths throughout the entire Hartha Formation, including the upper, middle, and lower parts, especially at well Ba-1 (Plate 2A).

b) Cementation

This process has negative effects on the primary and secondary porosity of the Hartha Formation. As a result, various types of cement are filling the intergranular and intragranular, as well as cavities, and fractures porosities within the wells under study. The main types of cementations observed at different depths within the Hartha Formation are blocky cement and granular cement (Plate 2B). This type of diagenetic process is typically concentrated at the upper part of the Hartha Formation.
Plate 2. Photomicrographs of microfacies in Hartha Formation. (A) Recrystallization in well Ba-1 at depth 1873m, X40. (B) Blocky cement in well Ba-6 at depth 1744m, X40. (C) Stylolitization process in well Ba-1 at depth 1685m, X40. (D) Dolomite crystals in well Ba-1 at depth 1916m, X40. (E) The effects of dissolution on Orbitoides Sp in well Ba-5 at depth 1950m, X40

c) Compaction and Pressure Solution (Stylolitization)

Compaction is commonly categorized into two main types: mechanical compaction and chemical compaction (Friedman and Sanders, 1978). Mechanical compaction involves the deformation and crushing of skeletal grains under the overburdened sediment load, leading to re-arrangements of the grains. However, this type of compaction is not specifically addressed in the present study. On the other hand, chemical compaction occurs when pressure dissolution causes serrated surfaces known as stylolite within the rock mass. These stylolites form as a result of sediment's overburden pressures and tectonics force (Ahmed and Jawad, 2020). The Hartha Formation has been particularly affected by chemical compaction, leading to the formation of stylolite, especially at the upper part of the Hartha Formation (Plate 2C).
4.2.2. Constructive diagenetic processes

a) Dolomitization

The dolomitization process takes place in two diagenesis stages: the early and late stages. The early stage is represented by the fine crystalline dolomite rhombs that are distributed with micritic groundmass. This type of dolomitization formed during the sediments deposition and it is not commonly observed in the studied wells. In contrast, the late stage is more prevalent in the current study. It is characterized by the coarse-grained dolomite crystals of euhedral to anhedral rhombs (Plate 2D), where the secondary porosity increases with the absence of compaction and cementation, therefore enhancing the reservoir quality (Chilingar and Wolf, 1967). The most dominant textures that have been observed in the studied wells are sucrose dolomite, spotted dolomite, fogged dolomite, and aphanotopic dolomite. Dolomitization has been observed in all parts of the Hartha Formation (upper, middle, and lower), leading to the development of high secondary porosity at various depths within the formation.

b) Dissolution

The dissolution processes have a significant impact on Hartha's succession. Dissolution has resulted in the formation of various types of pores, including vugs, moldic, and channels, which have enhanced the primary porosity (Plate 2E). The dissolution processes are predominantly observed in the lower part of the Hartha Formation.

4.3. Pore types

Porosity can be categorized into two types: primary porosity (sedimentary porosity), which is formed during the time of deposition and lithification, and secondary porosity (diagenetic porosity), which represents voids or spaces that develop after sediments deposition (Choquette and Pray, 1970; Selley, 1998). There are several types of pores have been recognized within the studied wells (Plate 3).

1. Interparticle Porosity

Interparticle porosity is originally a primary porosity type that formed during the time of deposition, but it can be enlarged by dissolution (Boggs, 2009). This type of porosity is very common in the grain-dominated microfacies of the Hartha Formation (Plate 3A).

2. Intraparticle Porosity

The intraparticle porosity represents the voids found within the grains or individual particles, especially within the skeletal grains. This porosity is not considered to be of genetic origin and it plays an important role in preserving porosity in carbonate rocks (Tucker and Wright, 1990). The most recognized intraparticle pores in the Hartha Formation are found within the internal chambers of fossils such as foraminifera and gastropods or other openings within individual or ordinary skeletal organisms (Plate 3A).

3. Intercrystal Porosity

Intercrystal porosity is the porosity between more or less equal-sized crystals that are frequently related to early and late diagenesis processes, such as recrystallization and dolomitization (Flügel, 2004). This type of porosity can have either a primary or secondary origin, and it is often distributed at different depths within the Harha Formation (Plate 3B).
Plate 3. Photomicrographs of microfacies in Hartha Formation. (A) Interparticle and Intraparticle porosity in well Ba-5 at depth 1907 m, X40, XPL. (B) Intercrystalline porosity in well Ba-1 at depth 2106 m, X40, XPL. (C) Moldic porosity in well Ba-8 at depth 1664 m, X40, PPL. (D) Vuggy porosity in well Ba-8 at depth 1660m, X40, PPL. (E) Channel porosity in well Ba-1 at depth 1698 m, X40, XPL. (F) Fracture porosity in well Ba-1 at depth 1698 m, X40, PPL.

4. Moldic Porosity

Moldic porosity is a form of dissolution porosity found in carbonate rocks. It occurs when crystals or skeletal structures, like foraminifers, algae, mollusk, and rudists, are partially or completely dissolved (Flügel, 2010). This type of porosity is very common and widely distributed within the present study (Plate 3C).

5. Vuggy Porosity

Vuggy porosity is a type of secondary porosity that develops through the dissolution of large features (macrofossils) within the grains to be visible to the naked eye during early and late diagenesis (Tucker and Wright, 1990). This type of porosity is widely distributed in different depths within the Harha Formation (Plate 3D).

6. Channel Porosity

This type of porosity is considered a non-fabric selective pore characterized by having longitudinal and branched pores that form as a result of the dissolution of the skeletal grains or other organisms (Flügel, 2004). This type of porosity is distributed in different depths within the Harha Formation (Plate 3E).

7. Fracture Porosity

This type of porosity is considered as a secondary porosity type that is formed by either plate tectonics forces and pressure solutions, or non-selective dissolution of the grains (Tucker and Wright,
1990). These pores are characterized by longitudinal fractures that can be either closed or opened, and they can also serve as permeable pathways, which contribute to the production of hydrocarbons (Selley, 1998). The fracture pores seen in the Hartha Formation under thin sections indicate that the fractures of the Hartha Formation can either be open or filled with calcite cement (Plate 3F).

4.4. Depositional Environments

The Hartha Formation at Balad oil fields exhibits three depositional environments: deep shelf margin, open shelf, and foreslope. Among these, the deep shelf margin and open shelf environments are the most dominant and widespread across different depths in the studied wells. On the other hand, the foreslope environment is less common and found only at specific depths within the wells. The distribution of facies within the wells is highly heterogeneous due to the influence of faults on the Hartha Formation, resulting in varying patterns (Figs. 4, 5, 6, 7, and 8). The mudstone microfacies indicate a deep shelf margin environment with low energy levels and quiet depositional conditions. The Wackestone, Wackestone to Packstone, and Packstone microfacies represent the open shelf environment, reflecting low to moderate and slightly high energy levels. Lastly, the packstone to grainstone and rudstone microfacies represent the foreslope environment, indicating high energy levels.
Fig. 4. Facies association succession and log response of Hartha Formation at well Ba-1.
Fig. 5. Facies association succession and log response of Hartha Formation at well Ba-5.
Fig. 6. Facies association succession and log response of Hartha Formation at well Ba-6.
Fig. 7. Facies association succession and log response of Hartha Formation at well Ba-7.
5. Conclusions

1. The Hartha Formation rocks in the Balad oil field contain six prominent microfacies that represent three distinct depositional environments: a deep shelf margin, an open shelf environment, and a foreslope environment.

2. The dissolution and dolomitization processes have a significant impact on the Hartha successions. Dissolution has resulted in the formation of various types of pores, including vugs, moldic, and channels, which have enhanced the primary porosity. Meanwhile, the dolomitization has led to create high secondary porosity at different depths within the Hartha Formation. Other diagenetic processes such as recrystallization, cementation, and Pressure Solution have destructive effects on porosity.

3. The deep shelf margin and open shelf environments are the primary and extensively distributed environments within the Hartha Formation. They cover a significant portion of this formation. On the other hand, the foreslope environment is less prevalent and is found at specific depths in the lower part of the Hartha Formation.
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