Linking diagenesis to sequence stratigraphy and its impact on reservoir quality of the Asmari Formation in Naft Sefid field, Dezful Embayment (SW Iran)

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Abstract

The present study has investigated relationship between diagenesis and sequence stratigraphy along with their effects on reservoir quality of the sedimentary microfacies. Detailed Microscopy observations of thin sections from core/cutting-bearing wells led to identification of fourteen microfacies, which are classified into three sub-environments of Inner ramp (tidal flat, lagoon), Middle ramp and Outer ramp. Inner ramp microfacies mostly observed in upper and middle parts of the Asmari Formation, while middle to outer ramp microfacies largely developed in middle part. The most important diagenetic processes controlling reservoir quality of the Asmari formation include neomorphism, compaction, cementation, dolomitization, dissolution and fracturing. Transgressive system tract (TST) microfacies in middle to outer ramp have been subjected to neomorphism, compaction, dissolution (moldic porosity) cementation and partly dolomitization. Based on petrophysical data with considering diagenetic imprints, seven reservoir zones are proposed for the Asmari Formation. Highstand system tract (HST) microfacies of inner ramp dominating the most part of reservoir zone 1 have been subjected to dolomitization, fracturing, minor compaction, and have better reservoir quality than the TST microfacies. Finally, correlation of the identified reservoirs zones has been investigated in the framework of third order stratigraphic sequences.

Keywords: Diagenesis, reservoir quality, sequence stratigraphy, Asmari Formation, Naft Sefid field, Dezful Embayment

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1. Introduction

The Oligo-Miocene carbonate successions of the Asmari Formation and its time-equivalents in the Persian Gulf considered as one of the most well-known petroleum systems of the Middle-East, especially in Iran and Iraq, which more than 90% of the recoverable hydrocarbons of Iran and Iraq (e.g. James and Wynd, 1965; Murris, 1980; Berberian and King, 1981; Motiei, 1993; Jassim and Goff, 2006). Overall, the Zagros basin contains about two-thirds of proven oil reserves and one-third of gas reserves in the world (e.g. Beydoun et al., 1992). The Asmari Formation (well-known as fractured carbonate unit) is the most prolific reservoir in at least 63 fields in Dezful Embayment including several supergiant and giant reservoirs such as Ahwaz, Marun, Gachsaran, Aghajari, Naft Sefid, SW Iran (Motiei,1993; Alavi, 2004). The most prolific reserves of the Arabian Platform and Zagros Basin hydrocarbon provinces (almost 400 billion barrels of oil-in-place and 7% of oil reserves in the world) produced from the Early Miocene Asmari carbonates and the Albian-Cenomanian Sarvak limestones (Bordenave, 2002; Rahimpour-Bonab et al., 2012).

Lithologically, the Asmari Formation mainly consists of limestones and dolomites, and some intervals of marl, shale, sandstone and evaporites can be seen in some parts of it; for example, Kalhur anhydrite in Lorestan and Izeh zones, and Ahwaz sandstone in southwest Dezful Embayment (Motiei,1993). In its type section (Tang-e Gel-e Torsh), it is composed of limestones, dolomitic limestones, and argillaceous limestones with the thickness of 314 m. However, its thickness varies from 100 to more than 500 m in the Dezful Embayment (Beydoun et al., 1992; Motiei, 1993).

More recent studies have been conducted on the biostratigraphy and lithological characteristics (e.g. James and Wynd, 1965; Adams and Bourgeois, 1967; Kalantari, 1986; Seyrafian et al.,
1996; Rahmani et al., 2009; Amirshahkarami et al., 2010; Rahmani et al., 2012), facies analysis and depositional environment and sequence stratigraphy (Nadjafi et al., 2004; Vaziri-Moghaddam et al., 2006; Amirshahkarami et al., 2007; Kavoosi and Sherkati, 2012), and isotope stratigraphy of the Asmari Formation (Ehrenberg et al., 2007; van Buchem et al., 2010). However, the relationship between the diagenesis and reservoir quality of this formation in a sequence stratigraphic context are still remained as a relatively unknown issue.

The quality and heterogeneity of carbonate reservoirs are dominantly associated with various controlling parameters including sedimentary environments, diagenetic agents, tectonic features, burial history of the basin, and timing of hydrocarbon migration (Choquette and James, 1987; Wang and Al-Aasm, 2002; Wierzbicki et al., 2006; Morad et al., 2012). Diagenetic key parameters such as cementation, dissolution and dolomitization have the most controls on heterogeneous distribution and evolution of reservoir quality of carbonate reservoirs (Wang and Al-Aasm, 2002; Morad et al., 2012). The integration of diagenesis and sequence stratigraphy can be applied as a useful tool for predicting sedimentary facies, temporal and spatial distribution of porosity and permeability in carbonate reservoirs (Moore, 2001; Tucker and Booler, 2002; Caron et al., 2005; Morad et al., 2012). This method can also justify the cause of compartmentalization of the mixed carbonate-evaporite reservoirs.

Accordingly, this study aims to (1) determine the main microfacies and their affecting diagenetic processes and (2) reservoir zonation of the Asmari Formation based on the linking diagenesis to reservoir quality in the sequence stratigraphic framework.
2. Geological setting and stratigraphy

From the Middle Eocene to Early Miocene, the Arabian Plate has affected the southern Asian Plate border resulted in the Zagros belt orogeny. The Zagros Basin, as a second largest basin in the Middle East, extends from Turkey, north-eastern Syria and north-eastern Iraq through north-western Iran and falls into south-eastern Iran. The Zagros orogens of Iran are divided into three principle tectonic units (Stocklin, 1968; De Jong, 1982) namely the Zagros fold-thrust zone, the imbricated zone and the Urumieh–Dokhtar magmatic zone (Alavi, 2004) (Fig. 1). The Zagros fold thrust belt is divided into several zones including Lurestan, Izeh, Dezful Embayment, Fars, High Zagros (Fig. 2), each of them have different tectonic context and sedimentary history (Berberian and King 1981; Motiei 1993). Generally, the Zagros zones including Dezful Embayment are considered as northeastern part of the Arabian Plate. These structures formed as a result of the Arabian-Eurasia collision during the Late Miocene to Pliocene orogenic stages (Stocklin, 1968). The Dezful Embayment was isolated from Lurestan and Fars provinces by the Kazerun fault (Falcon1974; Motiei 1993). It considered as a part of the Zagros fold-thrust belt, in which the Asmari Formation was best developed. Studied intervals of the Asmari Formation in this research are located in the Naft Sefid oil/gas field, Dezful Embayment (Fig. 1).

From the Late Cretaceous-Eocene, Dezful Embayment considered part of a NW-SE trending basin, which was possibly a remnant of the Late Cretaceous fore-deep basin. The basin was filled with carbonate sediments during the Oligocene and siliciclastic deposits (Ahwaz sandstones) in the southwestern part of the Dezful Embayment as well (Horbury et al., 2004).
Figure 1 (a) Major tectono-sedimentary subdivisions of the Iran (after Falcon, 1974), (b) Location of the Naft Sefid field in Dezful Embayment.

The influence of the siliciclastic input has been decreased towards the northern and central parts of the Dezful area so that there was deeper water basin (more subsidence rate) towards the northern parts of the Dezful Embayment, and then, the remaining basinal parts filled with the evaporitic deposits (i.e. Basal Anhydrite and Kalhur Member/ Middle Anhydrite) (Fig. 2). Convergence of the plates led to closing of the Neo-Tethys, and therefore, deposition of the thick evaporitic successions of Gachsaran Formation.

The base of the Asmari Formation is diachronous so that its base, towards the coastal Fars area, is mainly Rupelian in age; but in the Dezful Embayment, its age varies from Rupelian to Chattian (Motiei, 1993) (Fig. 2). The top of the Amari Formation is mostly Burdigalian in age, but, toward the coastal and interior Fars, it has Chattian age. For instance, although the Oligocene deposits of the Asmari Formation have been reported from some outcrops (e.g., Tang-
e-Gurgudan outcrop), and many oil-fields (e.g., Ahvaz, Ab-Teymur, Rag-e-Sefid) in SW Iran, they have not been deposited in northern oil-fields of Dezful Embayment (such as Naft Sefid and Haftkel) (e.g. van Buchem et al., 2010). In other words, in the latter fields, deposition of the Asmari succession began in chattian stage overlaying the Pabdeh Formation with the basal anhydrite layer, and overlaid by the Gachsaran evaporitic cap rock.

![Figure 2](image)

**Figure 2** Stratigraphic column of the Oligo-Miocene rock units in the Dezful Embayment, Izeh Zone and High Zagros, Zagros basin (modified from van Buchem et al., 2010)

### 3. Materials and methods

Geological data from two exploratory wells (NS-A, NS-B) in the Naft Sefid Field were used for this study. A total of 1620 standard thin sections from core and cutting samples were investigated for petrographic purpose. Microfacies analysis and depositional setting of the samples were done based on Dunham (1962) and Flügel (2004, 2010) classifications.
The reservoir rock types of Lucia classification (1995) were determined through the integration of depositional facies, diagenetic imprints and petrophysical data. Then, the main controlling factors affecting the reservoir quality (i.e. depositional textures and diagenetic imprints) were determined in framework of the depositional sequences. Finally, the proposed reservoir zones of the Asmari Formation in the studied wells were correlated in the sequence stratigraphic framework.

4. Facies analysis

Detailed petrographic analysis of the cores, cutting and thin sections allowed the identification of fourteen (one non-carbonate/ anhydrite and thirteen carbonate) microfacies. Distribution of microfacies along with their interpreted depositional characteristics indicates a gradual change from inner ramp to outer ramp sub-environments of a homoclinal carbonate ramp (Soltani et al., 2013). The major identified microfacies are shown in Figures 3 and 4. In the studied intervals, the inner ramp facies (dolomitized mudstone (MF2) and echinoid wackestone (MF5)) are the main constituents of the Asmari Formation while sandy wackestone (MF4) and faverina packstone (MF12) microfacies have the least frequency.

5. Diagenesis

The diagenesis usually decreases porosity through filling of the available pore spaces by various forms of cementation and mineral growth; however, it can cause increasing porosity by leaching of the grain matrix (dissolution) and produce secondary pore spaces; dolomitization processes can also led to increase, create, reduce, redistribute and preserve porosity (Alsharhan, 1995; House, 2007). Distribution of the diagenetic parameters as a function of their stratigraphic position, depositional environment and sedimentary texture determines the ultimate nature of the rock fabrics, and therefore, their reservoir quality.
Neomorphism, micritization, compaction, cementation, dolomitization, dissolution and fracturing are the main diagenetic processes, which modified the primary reservoir quality of the Asmari Formation in the studied wells of Naft Sefid field. Neomorphism was frequently occurred as transformation of high-Mg calcite into equant calcite spar and recrystallization of the mud-dominated fabrics. This process has less importance and uncertain role on reservoir quality in the studied successions.

Micritization, as a common marine diagenetic process, is observed as thin micritic envelopes around carbonate allochems in most grain-supported facies (e.g., MF7 to MF9) (Fig. 3). This syn-depositional process caused the more mineralogical stability of the grains against the compaction and cementation, which prevented porosity loss during burial diagenesis.
Dolomitization is another process widely occurred in the upper part of the Asmari Formation, which led to create/increase in porosity/permeability. This process is the key parameter controlling reservoir quality, which possibly occurred during reflux of saline brines originated from Gachsaran Formation (cf. Ehrenberg et al., 2007).

Dissolution is one other diagenetic process, which affected the porosity and permeability. This process caused the creation of moldic porosity in the upper part of the succession (Fig. 5 C). Dissolution is observed as preferential leaching of compositionally unstable components such as aragonitic allochems of *Borelis melo curdica* and gastropods, which subjected to undersaturated meteoric pore fluids.

Cementation by anhydrite and calcite is another destructive post-depositional process, which observed in different types such as fracture-filling, poikilotopic, pore-filling and drusy/blocky forms (Fig 5 E-H). Both physical and chemical compactions, which resulted in reducing porosity and permeability of the facies, are observed in the studied thin sections. Physical compaction led to the reorientation of grains in some mud-supported microfacies (Fig. 5-D). Chemical compaction developed as stylolite within both grain and mud dominated facies (Fig. 5-D).

Fractures observed in various scales in the studied wells. They are mostly associated with compacted and stylolite bearing mud-dominated microfacies, i.e. mudstones and wackstones. Fracturing is best developed in dolomitized microfacies (Fig. 5-A). In many samples, fractures are filled with anhydrite and calcite cements. Fracturing appears to be the last diagenetic event in the Asmari succession, in which fractures have cut the stylolites, unless in rare samples filled with anhydrite cement (Fig. 5-F).
Figure 5 Main diagenetic processes affecting the reservoir quality of the Asmari Formation in the studied wells; (A) dolomitization, (B) fracturing, (C) dissolution (moldic porosity), (D) mechanical compaction and stylolite, (E) Poikilotopic anhydrite cement, (F) fracture-filling anhydrite cement, (G) drusy calcite cement infilling bivalve bioclast, and (H) blocky calcite cement within bioclast.

6. Reservoir quality and zonation

The reservoir quality of carbonate facies is mainly controlled by the combination of primary (texture, fabric, grain size, mineralogical composition) and secondary (diagenetic) properties
(Ahr, 2008; Lucia, 1995; 2007). In this section, according to petrophysical classification of Lucia (1995), the relationship between porosity and permeability are shown by different rock fabric classes (Fig. 6). Various depositional facies of the Asmari Formation influenced by different diagenetic processes resulted in different amounts of porosity and permeability (Fig. 6). Accordingly, in this research, reservoir zones are determined with considering the depositional characteristics and the most effective diagenetic imprints (dolomitization, anhydrite cementation, dissolution and fracturing) controlling reservoir quality of the studied wells (Fig. 6 and Table 1).

![Figure 6](image)

**Figure 6** Poro-perm cross-plot of the Asmari Formation in the studied wells (triangles: well-A, and circles: Well-B) representing high reservoir quality of lagoon and outer ramp microfacies resulted from dolomitization (pink-dashed circle), fracturing and dissolution (brown-dashed oval range). Lower quality in these rock fabrics is due to cementation (mainly anhydrite) and compaction (red-dashed oval range).

In the studied wells, porosity resulting from the dissolution of allochems and permeability from dolomitization and fracturing caused enhancing reservoir quality of the Asmari Formation. Compaction and cementation (calcite/ anhydrite) led to decrease in the reservoir quality. Given that the microscopy observations and porosity-permeability cross plot, dolomudstone (MF3),
echinoid wackestone (MF5) and peloidal packstone (MF7) represent better reservoir quality in the Asmari interval (Fig. 8), which widely influenced by dolomitization (development crystalline porosity) and fracturing (increase in permeability).

Despite of low values of matrix porosity (less than 10%), in some oil fields of Dezful Embayment (e.g. Gachsaran oil field), up to 80,000 barrels of oil per day are produced from the fractured dolomitized limestone (McQuillan, 1985). The more occurrence and intensity of fracturing in dolomitized microfacies than the limestones is thought to higher fragility of dolomite (Ahr, 2008). In addition, the dolomites have higher resistance to compaction (Moore, 2001), and therefore, undergo less reservoir quality loss with depth than limestones (Amthor et al. 1994). Fractures in the Asmari sequences are partially filled with anhydrite cements; however, in cases they have not been filled and increased permeability. The main destructive processes are cementation (anhydrite/ calcite) and compaction, which have significantly decreased porosity and permeability of the Asmari reservoir in the studied wells (Fig. 8).

Based on depositinal microfacies, rock fabrics and their petrophysical characteristics, and considering diagenetic impacts, seven reservoir zones have been determined for the Asmari Formation in the wells NS-A and NS-B of the Naft Sefid Field (Table 1 and Fig. 8). As given in table 1, the Zone 1 represents the best reservoir quality in the studied wells. Also, the values of porosity and permeability decrease from Zone 1 to Zone 7 in well NS-B.
Table 1 Determined reservoir zones based on the average values of porosity and permeability in the wells NS-A and NS-B.

<table>
<thead>
<tr>
<th>Reservoir Zone</th>
<th>NS#A</th>
<th>NS#B</th>
<th>Main lithology</th>
<th>Average Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>9.15</td>
<td>10.68</td>
<td>Dol./ Lst.</td>
<td>58</td>
</tr>
<tr>
<td>Zone 2</td>
<td>6.2</td>
<td>8.66</td>
<td>Dol./ Lst.</td>
<td>52</td>
</tr>
<tr>
<td>Zone 3</td>
<td>No Data</td>
<td>6.95</td>
<td>Dol./ Lst.</td>
<td>38</td>
</tr>
<tr>
<td>Zone 4</td>
<td>No Data</td>
<td>9.4</td>
<td>Lst. (mostly)</td>
<td>13</td>
</tr>
<tr>
<td>Zone 5</td>
<td>No Data</td>
<td>5.3</td>
<td>Middle Anhydrite</td>
<td>18</td>
</tr>
<tr>
<td>Zone 6</td>
<td>No Data</td>
<td>3.3</td>
<td>Lst./ Dol.</td>
<td>32</td>
</tr>
<tr>
<td>Zone 7</td>
<td>No Data</td>
<td>1.7</td>
<td>Shale/ Marl</td>
<td>71</td>
</tr>
</tbody>
</table>

7. Linking between diagenesis and sequence stratigraphy

Sequence stratigraphic investigations led to the determination of three third-order sequences (Fig. 8); the two first sequences (the equivalent of sequences 4 and 5 introduced by van Buchem et al., 2010) are Aquitanian in age (Early Miocene), which their deposition started with lowstand subaqueous anhydrites (i.e. Basal Anhydrite and Middle Anhydrite/ Kalhur Member). The third sequence (the equivalent of sequence 6 by van Buchem et al., 2010) has Burdigalian age (Middle Miocene) and represents the last stage of the Neo-Tethys closure marked by shallow water evaporitic condition (deposition of Gachsaran Formation) (Fig. 8).

Due to the lack of petrophysical and core data in the middle-lower part of the Asmari Formation in well NS-A, only two reservoir zones in the uppermost part of the Asmari succession (sequence 6 with Burdigalian age) are discussed as following.

Reservoir Zone 1 (RZ-1): This zone is about 58 m thick in the studied wells and corresponds with the upper part of the Asmari Formation (HST of sequence 6), the upper boundary of which is overlaid by member 1 of the Gachsaran Formation (Fig. 8). Dolomite and limestone constitute the main body of this zone. According to the rock fabric classification of Lucia (1995), reservoir
zone 1 lies mainly in the class 3 with permeability range of less than 20 microns (Fig. 7a). The average values of porosity and permeability in this zone are 9.9 % and 0.65 md, respectively. This reservoir zone shows the best reservoir quality in which lagoonal to tidal flat microfacies (dolomitized mudstone and echinoid wackestones) of the inner ramp are dominant. The major part of the reservoir quality of this zone is associated with the post-depositional processes of extensive dolomitization, fracturing and dissolution (Figs. 7a, 8 and 9).

Reservoir Zone 2 (RZ-2): This zone is mainly composed of limestone and dolomite, which belong to the TST of sequence 6. The average thickness of this zone in the studied interval is about 51 m. The major components of this zone are related to inner ramp microfacies (lagoon to outer ramp). This zone has a lower reservoir quality than zone 1 (Table 1); the porosity and permeability mean values are 7.4 % and 0.16 md, respectively. This resulted from the destructive impacts of compaction (stylolitization) and anhydrite cementation, as well as limited dolomitization (Figs. 7b, 8 and 9). Based on the Lucia’s classification (1995), this zone falls into the classes 1 and 2 (dolomitized packstones to grainstones) with a permeability range of 20 to 500 microns (Fig. 7b).
**Figure 8** Sedimentological characteristics and generalized reservoir zones (RZ1-RZ7) of the Asmari Formation within sequence-stratigraphic framework; the upper part of Asmari succession equals to RZ1-2 shows the best reservoir quality in the correlated studied wells.
8. Conclusion

The Asmari Formation in the Naft Sefid field has variable thickness of about 200 to 400 meters, which deposited in a carbonate homoclinal ramp. The most sedimentary thickness of Asmari Formation in this field is associated with the inner ramp and somewhat the middle-outer ramp microfacies. Seven reservoir zones were determined for the Asmari Formation based on the depositional characteristics, diagenetic imprints and petrophysical rock fabrics. The major part of the reservoir quality observed in zone 1 and 2 (i.e. inner ramp microfacies). High-stand system tract (HST) was found the best reservoir quality in comparison to transgressive system tract (TST), which resulted from the constructive impacts of dolomitization, fracturing and dissolution.
processes. Inner ramp microfacies in the high-stand system tract were mainly affected by total dolomitization, fracturing, and selective (moldic) dissolution. Middle-outer ramp microfacies of the transgressive system tract (TST) were influenced by compaction, dissolution, cementation and partial dolomitization.

References