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Abstract
The Oligo-Miocene Asmari Formation is the most prolific reservoir in the Dezful Embayment, south-west of Iran. Depositional and diagenetic effects on reservoir quality in the sequence stratigraphic framework were carried out on the basis of petrographic investigation, petrophysical logs, and core measurement porosity and permeability data. Petrographic analysis resulted in the identification of 12 microfacies classified in 5 sub-environments including tidal flat, lagoon, barrier, shallow open marine and basin, which indicate deposition in a homoclinal ramp setting. Tidal flat, lagoonal and barrier microfacies are mostly present in the upper and middle parts of the Asmari Formation, while outer ramp microfacies largely developed in the middle part. Anhydrite and calcite cementation, compaction, dolomitization, dissolution, and fracturing are the main diagenetic controlling factors on petrophysical properties. Fracturing, dolomitization, and dissolution are contributed to reservoir quality enhancement, while compaction and cementation had negative effects on reservoir quality. The studied successions are represented by 3 third-order sequences of early Aquitanian, late Aquitanian and early Burdigalian ages that largely deposited in the highstand systems tract (HST) stage.

Keywords: Asmari Formation; Dezful Embayment; Microfacies, Diagenesis, Reservoir Quality.

Introduction
Carbonate reservoirs are more complicated than clastic reservoirs (Ahr, 2008). Petrophysical properties in carbonate rocks are affected by depositional geometry, lithological variation and diagenetic modifications (Lucia, 2007 & Ahr, 2008). Depositional facies is dictated by carbonate platform geometry that, in turn, controls the diagenetic regime (Ehrenberg et al., 2007). Relative sea-level variations and sequence stratigraphic framework affect carbonate platform geometry (Hollis & Sharp, 2011). Herein, we attempt to obtain an improved comprehension of carbonate reservoir heterogeneities of the Asmari Fm. to propose the sequence stratigraphic framework for further reservoir quality assessment. The Oligo-Miocene Asmari deposits in the Zagros area are among the well-known hydrocarbon producing intervals in the world. This formation has the most thickness in the Dezful Embayment (e.g. Alavi, 2004). These carbonate platform successions comprise giant and supergiant reservoir fields in SW Iran and NE Iraq. Comprehensive lithostratigraphic and microfacies studies of Asmari Formation have been conducted by James and Wynd (1965) and Sampo (1969), respectively. Recently, numerous works have been published on the Asmari Formation, but many of them of a more local nature. These works focused on biostratigraphy (Seyrafian & Hamedani, 2003), depositional environment (Vaziri- Moghaddam et al., 2006), diagenesis (Aqrwi et al., 2006), isotopic dating (Ehrenberg et al., 2007; Mossadegh et al., 2009), reservoir rock typing (Moradi et al., 2017; Farshi et al., 2018), and sequence stratigraphy (Avarjani et al., 2015; Daraee et al., 2017). Despite all these studies, lack of a study linking reservoir quality to the depositional environment and diagenetic features especially in the study area is felt. Regarding that, the main purposes of this research are: to define facies types and depositional setting of the Asmari Formation, to determine the major diagenetic imprints and their effects on reservoir quality, and correlate the diagenetic trends in the studied field within the framework of sequence stratigraphy.

Geological context
The Zagros Mountains resulted from the multi-phase collision of the Arabian shield with the Iranian microplate (Berberian & King, 1981; Sepehr & Cosgrove, 2004). It is divided to imbricated thrust zone, and folded belt (Sherkati & Letouzey, 2004) (Fig. 1). The folded belt is marked by asymmetrical anticlines with NW-SE trends, and includes Dezful and Kirkuk Embayments, Lurestan, Izeh, Abadan Plain and Bandar Abbas hinterland (Fig. 1) (Sepehr & Cosgrove, 2004). Dezful
Embayment is considered as a part of the Zagros fore-deep that is limited to the Kazerun fault to the east, and Balarud flexural zone to the north. This area consists of 15 km thick sediments from Paleozoic to recent (Motiei, 1993).

The Oligo-Miocene Asmari Formation overlies the Pabdeh shale, and is overlain by the Gachsaran evaporites (Fig. 2). It is well-developed throughout the Zagros area unless the Bandar Abbas region. In the late Oligocene, north parts of Lurestan and Fars were exposed, but the Ahwaz sandstone member was deposited in the Khuzestan area (Dezful Embayment). Simultaneously, the Kalhur evaporitic member, as a part of the middle Asmari, was deposited in the Lurestan Province. In the Aquitanian stage, shallowing-upward cycles of the middle Asmari Formation were deposited throughout the basin. By the end of this depositional cycle, the shallow water condition was developed leading to the dolomitization of the middle Asmari sequences (Aghanabati, 2004 & van Buchem et al., 2010). Subsequently, through the widespread transgression of the Burdigalian Sea, the upper Asmari sequence has been deposited, and at the end of the Burdigalin stage, the Asmari depositional cycle was terminated due to the significant sea-level dropping stage. As a consequence, the dominant evaporative condition was governed over the basin (Aghanabati, 2004).

The studied field is an NW-SE anticline, which is placed in the northeastern Dezful Embayment (the Central Zagros Basin) (Fig. 1). The Asmari Formation is considered as a key reservoir in the field. In this field, the Asmari mainly contains carbonate-evaporite facies, and the lower part of the Asmari (equivalents to the sequences 1 to 3 of van Buchem et al., 2010) has not been deposited. Basal anhydrite of the Asmari Formation overlaid directly the Pabdeh marls, and the Gachsaran cap rock, conformably overlaid the Asmari carbonates (Fig. 2).

Figure 1. Main structural subdivisions of the Simply Folded Zagros Belt (Alavi, 2004). The studied oil-field is located in Dezful Embayment.
Materials and methods

Data from four exploration wells from one of the oilfield in the Dezful Embayment, northeast of Ahwaz City has been collected for this research (Fig. 1). The Asmari Formation has a different thickness between 280 m (well C) and 350 m (well A). Close sampling and high-resolution microscopic studies (4872 thin sections from four wells; Well A, 1472 samples; Well B, 1400 samples; Well C, 800 samples and Well D, 1200 samples) are conducted to define main depositional microfacies of the formation. Some thin sections were stained with Alizarin Red-S through standard approach (Dickson, 1965), among which 400 samples were also impregnated by blue-dyed resin to examine pore space properties. Facies nomenclature was done according to a modified Dunham (1962) classification along with diagnostic allochems, mineralogical composition, and grain size. More detailed facies analysis was conducted based on standard microfacies schemes (e.g., Flügel, 2004). A schematic depositional model was proposed for the Asmari Formation in the study area and the effect of facies distribution on reservoir quality development was discussed.

Porosity and permeability from cores of two wells (B and D) including 1300 core porosity – permeability along with wireline logs of four wells (A, B, C, and D) were also available for this study. The main sequences and startal surfaces were recognized based on microfacies properties, their sedimentary environment and deepening and shallowing trends in the microfacies vertical arrangement. Identification of the sequences was based on (van Wagoner et al., 1990; Vail, 1990), where each sequence is restricted between two sequence boundaries in the lower and upper part and maximum flooding surface (MFS) distinct transgressive systems tract (TST) from high stand systems tract (HST). Finally, the relationship between recognized sequences and systems tract with petrophysical properties (porosity and permeability) and how the reservoir quality changes during its deposition is determined.

Results

Facies Analysis

Results from petrographic investigation allowed the recognition of 12 microfacies, which were classified into five facies belts. The main characteristics and their depositional setting of the recognized microfacies are represented in Table 1 and Figure 3.

Anhydrite (MF1): It is observed as chicken-wire structure, parallel lamination and coalesced nodules (Fig. 4-A) and occurs in two horizons (Kalhor Member and Gachsaran Formation). It plays the role of a seal for the studied interval of the Asmari Formation. The anhydrite probably precipitated in a
A hypersaline lagoon/sabkha environment (e.g., Alsharhan & Kendall, 1986; Lucia, 2007). The existence of supratidal evaporates and anhydrites indicates that the facies was deposited in an arid and warm climate (Flügel, 2004) (Table 1).

<table>
<thead>
<tr>
<th>Age</th>
<th>Formation</th>
<th>Depth (m)</th>
<th>Lithology</th>
<th>Depositional texture</th>
<th>Depositional Environment</th>
<th>Sequence stratigraphy</th>
<th>Diagenetic Processes</th>
<th>Pore type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oligo-Miocene</td>
<td>Upper Asmari</td>
<td>1700</td>
<td>Mudstone</td>
<td>Total flat</td>
<td>Restricted lagoon</td>
<td>Relative sea level change</td>
<td>Solution</td>
<td>Intergranular</td>
</tr>
<tr>
<td></td>
<td>Middle Asmari</td>
<td>1750</td>
<td>Wackestone</td>
<td>Restricted lagoon</td>
<td>Restricted lagoon</td>
<td>Relative sea level change</td>
<td>Solution</td>
<td>Intergranular</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1800</td>
<td>Pebblestone</td>
<td>Restricted lagoon</td>
<td>Restricted lagoon</td>
<td>Relative sea level change</td>
<td>Solution</td>
<td>Intergranular</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1850</td>
<td>Pebblestone</td>
<td>Restricted lagoon</td>
<td>Restricted lagoon</td>
<td>Relative sea level change</td>
<td>Solution</td>
<td>Intergranular</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1900</td>
<td>Carbonate</td>
<td>Restricted lagoon</td>
<td>Restricted lagoon</td>
<td>Relative sea level change</td>
<td>Solution</td>
<td>Intergranular</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1950</td>
<td>Bandedstone</td>
<td>Restricted lagoon</td>
<td>Restricted lagoon</td>
<td>Relative sea level change</td>
<td>Solution</td>
<td>Intergranular</td>
</tr>
</tbody>
</table>

Figure 3. Lithology, log response, sedimentary facies, identified sequence and diagenetic features of the well B in the studied field.
Table 1. Main recognized microfacies of the Asmari succession in the studied oil field.

<table>
<thead>
<tr>
<th>Microfacies</th>
<th>Code</th>
<th>Main Allochems</th>
<th>Facies belt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive Anhydrite</td>
<td>MF1</td>
<td>-</td>
<td>Supratidal</td>
</tr>
<tr>
<td>Anhydrite bearing mudstone</td>
<td>MF2</td>
<td>Gastropod, benthic forams, echinoid</td>
<td>Supratidal to intertidal</td>
</tr>
<tr>
<td>Dolomudstone</td>
<td>MF3</td>
<td>-</td>
<td>Intertidal</td>
</tr>
<tr>
<td>Quartz-bearing wackestone</td>
<td>MF4</td>
<td>Gastropod, ostracod, miliolid</td>
<td>Lagoon</td>
</tr>
<tr>
<td>Echinoid wackestone</td>
<td>MF5</td>
<td>Echinoid, miliolid, textularia, red alga fragments</td>
<td>Lagoon</td>
</tr>
<tr>
<td>Benthic frominifera wacke to packstone</td>
<td>MF6</td>
<td>Benthic forams (miliolid, <em>Borelis</em>, <em>Peneroplis</em>, <em>Dendritina rangi</em>), ostracod</td>
<td>Restricted lagoon</td>
</tr>
<tr>
<td>Peloidal wacke to packstone</td>
<td>MF7</td>
<td>Peloid, miliolid, ostracod</td>
<td>Lagoon</td>
</tr>
<tr>
<td>Benthic frominifera pack to grainstone</td>
<td>MF8</td>
<td>Peloid, benthic foraminifera, gastropod</td>
<td>Leeward shoal</td>
</tr>
<tr>
<td>Coral boundstone</td>
<td>MF9</td>
<td>Coral</td>
<td>Shoal</td>
</tr>
<tr>
<td>Algal wackestone</td>
<td>MF10</td>
<td>Coralline algal, bivalve, gastropod</td>
<td>Middle ramp</td>
</tr>
<tr>
<td>Faverina packstone</td>
<td>MF11</td>
<td><em>Faverina</em>, peloid</td>
<td>Open marine</td>
</tr>
<tr>
<td>Planktonic foraminifera wacke to mudstone</td>
<td>MF12</td>
<td><em>Globigerinids</em>, <em>Ditrupa</em></td>
<td>Basin</td>
</tr>
</tbody>
</table>

Figure 4. The main microfacies types of the Asmari Formation in the studied wells: A) Anhydrite, B) Anhydrite bearing mudstone, C) Dolomudstone, D) Quartz-bearing wackestone, E) Echinoid wackestone, F) Benthic foraminifera wacke to packstone.
Anhydrite bearing mudstone (MF2): The major components include fossil fragments of gastropod, miliolid, rotaliids, and echinoid (Fig. 4-B). Scattered anhydrite patches are observed in pore-filling and nodule forms. Its sedimentological nature indicates a supratidal to intertidal setting affected by hypersaline waters (Flügel, 2004) (Table 1).

Dolomudstone (MF3): The facies has not any observable allochems (Fig. 4-C). Dolomite crystals are identified with types of non-planar to planar textures. Microbial and fenestral fabrics are also observed in this facies. Anhydrite nodules are present (Fig. 4-C). The main porosities include fenestral, intercrystalline and interparticle pores.

Quartz-bearing wackestone (MF4): It contains sand-sized quartz grains within a micrite matrix (Fig. 4-D). The quartz grain is possibly deposited during the lowstand levels of the basin through windy currents. Fossil contents such as some benthic foraminifera, gastropods, and ostracods indicate a low energy shallow-marine setting (Flügel, 2004) (Table 1).

Echinoid wackestone (MF5): The major constituents include echinoids and rotaliids as well as other fossil fragments of benthic foraminifera (Fig. 4-E). This facies can be attributed to the low energy setting of a lagoonal condition (Flügel, 2004) (Table 1).

Benthic foraminifera wacke to packstone (MF6): Benthic foraminifera including miliolids, Peneroplis sp., Borelis melo eurdica, Dendritina sp., and Archias sp. constitute the main skeletal grains of this microfacies (Fig. 4-F). The presence of fossil content and characteristics of this facies reveal the restricted lagoon setting (Flügel, 2004) (Table 1).

Peloidal wacke to packstone (MF7): It mainly contains peloids, some fragments of miliolids, ostracods, and quartz grains (Fig. 5-A). Its depositional condition can be assigned to shallow and medium energy part of the lagoonal setting (Flügel, 2004) (Table 1).

Benthic foraminifera packstone to grainstone (MF8): The mainly contains benthic foraminifera and minor constituents such as peloid, gastropod and algal fragments (Fig. 5-B). Abundance of benthic foraminifera and medium sorting of grains indicate relative reworking of allochems and their deposition in a shallow high energy condition of back-shoal to the proximal of the middle ramp setting (Flügel, 2004) (Table 1).

Coral boundstone (MF9): The major skeletal components are coral, and some bryozoan along with echinoid fragments (Fig 5-C). The occurrence of this facies is to appear mainly as a patch reefs in the studied field. The depositional setting of these reef bodies can be assigned to the distal part of the inner ramp (Flügel, 2004) (Table 1).

Algal wackestone (MF10): The main constituents are corallinacean algae and some coral fragments within a micritic context. Minor skeletal grains including rotaliids, Miogypsina, echinoid, bivalve, and miliolid are observed (Fig. 5-D). The textural characteristics represent the middle ramp setting (Flügel, 2004) (Table 1).

Faverina packstone (MF11): The Faverina asmarica is the major constituent along with rare peloid and some benthic foraminifera (Fig. 5-E). Faverina is a type of fecal pellets generated by a marine crab and found in shallow marine carbonates of Mesozoic, sandy limestones of Jurassic and restricted lagoon deposits of Cretaceous (James & Wynd, 1965; Van Buchem et al., 2010). This facies represents the marginal marine setting of the basin (van Buchem et al., 2010) (Table 1).

Planktonic foraminifera wackestone to mudstone (MF12): Globigerina and minor fossils such as ostracod and Ditrupa are the main components (Fig. 5-F). Fine grains quartz and pyrite are also present in the micritic matrix. Based on the fauna and textural characteristics, this facies is attributed to deeper parts of the basin (outer ramp/basin) (Flügel, 2004) (Table 1).

Diagenesis
To understand the reservoir quality of the Asmari Formation and its evolution during the post-depositional period, the diagenetic history of the Formation is depicted next to the facies analysis. The main detected diagenetic overprints are calcite...
and anhydrite cementation, physical and chemical compaction, dolomitization, dissolution, and fracturing which are related to marine, meteoric and burial diagenetic realms.

**Diagenetic processes**

**Calcite cementation**

This is one of the mostly recorded diagenetic overprints in the limy parts of the studied Formation. Various phases of calcite cementation are detected within the Asmari succession. Moreover, there are several traces of these cements in dolomitic parts of the section which mainly indicate pre-dolomitization calcite cementation (meteoric and burial).

The identified calcite cementation phases can be grouped into three main categories as marine, meteoric and burial, which are differentiable from each other by using their fabrics and morphologies.

Figure 5. Continued the main microfacies types of the Asmari Formation in the studied wells: A) Peloidal wacke to packstone, B) Benthic foraminifera pack to grainstone, C) Coral boundstone, D) Algal wackestone, E) Faverina packstone, F) planktonic foraminifera wacke-mudstone.
- Isopachous marine calcite cementation
Among different types of marine cements (e.g. Moore, 2001), the only detectable type in the studied samples is isopachous (Fig. 7A). The isopachous calcite cementation is rare and observed in grain-supported facies (MF8) which developed around ooids and other allochems. However, in the dolomitized grain-dominated facies there are some traces of this cement which due to the dolomitization are faded.

This process is the result of chemical precipitation of CaCO3 via seawater pumping into the grain-dominated facies in normal marine condition (Moore, 2001). Therefore, the distribution of marine cementation is generally controlled by wave energy, rates of sedimentation and initial sediment porosity. The intensity of early marine cementation decreases from shoal setting toward the land and offshore (Fig. 6). This type of cementation helps to porosity preservation in burial and late diagensis.

- Syntaxial calcite overgrowth
This is visible as a rim of calcite crystals have grown by the extension of the lattice in allochems such as echinoids (Fig. 7B). These rims are mostly observed in echinoid wackestone microfacies and mainly concentrated in the upper part of the studied section (Fig. 3).

This cement type is not diagnostic of a particular diagenetic realm (Adams & MacKenzie, 1998) and reported from different diagenetic realms such as marine and meteoric phreatic to burial (e.g. Moore, 2001).

- Drusy and equant calcite cementations
These calcite cementations are mainly recognized as intergranular and pore-fillings (Fig. 7C). Also, there is a close relationship between them. They are reported from both grain- and mud-dominated facies. The grain-dominated facies are composed of both intergranular and pore-filling types, but the mud-dominated facies are included of pore-filling (intra-fossil or chamber filling) type. These cements are distributed through the Asmari Formation (Fig. 3).

These cements are defined as a product of dissolution and cementation in phreatic-meteoric to burial realms (Moore, 2001; Scholle & Ulmer-Scholle, 2003).

- Blocky calcite cementation
The coarse crystalline calcite cementation with sharp cleavages is defined as blocky calcite cement (Fig. 7D). This pore and fracture filling calcite cement is recognized through all parts of the Asmari Formation (Fig. 3). Blocky calcite cement is a product of burial diagenesis realm (Moore, 2001; Scholle & Ulmer-Scholle, 2003).

- Neomorphism
The neomorphic calcite cement or pseudo-spar is visible in several parts of the studied formation of the Field. However, it is more evident in mud-dominated facies and includes recrystallized micritic matrix (Fig. 7D). Moreover, the fine crystalline and micritic allochems (such as peloids and ooids) of the limy intervals show neomorphic cement and recrystallization (Fig. 7A).

Figure 6. Schematic depositional model of carbonate ramp showing the distribution of microfacies associations and the related depositional environments of the Asmari Formation in the studied oil-field, SW Iran.
These cement types are interpreted as meteoric or deep burial diagenetic phase (Folk, 1965; Al-Aasm & Veizer, 1986) or only a burial phase (Tucker & Wright, 1990).

**Anhydrite cementation**

Anhydrite is a minor (diagenetic) phase in the studied cored interval of the Asmari Formation (Fig. 3). This mineralogy is mainly related to dolomitic parts of the Formation. However, because of its negative effect on the reservoir quality it is among the most important diagenetic imprints recorded within the studied succession.

It must be noted that there is rare features of the primary anhydrite precipitation (syn-depositional) in the studied successions and most of the detected anhydritic parts are post-depositional.

In general, two types of anhydrite cements are recognized in the Asmari Formation of the studied Field including (Figs. 8A and B): 1- Replacive and pore-filling, and 2- Fracture filling.

The replacive and pore-filling anhydrite cementations are visited as fillings of bioclasts’ chambers, molds and vugs and replacements in both grain- and mud- dominated facies (Figs. 3 and 8A). The fracture filling type of anhydrite cement is reported from some parts of the studied intervals (Fig. 3).

Seemingly, these phases and types of anhydrite cementation are related to hypersaline fluids and also remobilization of previously precipitated anhydrite (both depositional and diagenetic; Husain and Krouse, 1978).

**Dissolution**

The dissolution related features such as molds and vugs (Fig. 8C) are prominent in the studied Asmari interval of the Field and sometimes are plugged by later cementation (Fig. 3).

Deposition of the Asmari Formations in shallow parts of a ramp (Fig. 6), made them very sensible to sea-level fluctuations. During several relative sea-level falls (Fig. 2), various parts of the studied platform were emerged and altered by meteoric waters (e.g. van Buchem et al., 2010). During these times, the deposited carbonates and also grains with high solubility mineralogies (e.g. gastropod, bivalve, and benthic foraminifera) are dissolved (Moore, 2001 & Tucker, 2001)

**Compaction**

Physical or mechanical compaction caused
reorientation or deformation of bioclasts especially in mud-supported microfacies and intervals of the studied Asmari Formation (Fig. 8D). These features are mainly reported from the upper part of the studied interval (Fig. 3). Features of chemical compaction including solution seams and stylolites as one the most visible diagenetic features in the Asmari Formation (Fig. 8E and 8F) are visible within both grain and matrix-dominated microfacies (Fig. 3).

Physical or mechanical compaction starts immediately after deposition and is driven by the effective stress applied on the sediments. However, overpressure reduces or stops mechanical compaction (Tucker, 1994). However, this process needs tens of hundred meters of burial (Bathurst, 1987).

Figure 8. Continued (A) Pore-filling anhydrite, XPL.. (B) Fracture-filling anhydrite cement, XPL., (C) Dissolution, which resulted in producing moldic porosity, XPL., (D) Mechanical/Physical compaction in Mud-dominated microfacies, XPL., (E) Solution seam, PPL. (F) Stylolite, PPL.
**Dolomitization**
Dolomitization is one of the most important diagenetic alterations in the Oligocene-Miocene successions of Zagros, both in view of frequency and controls on reservoir properties (e.g. Aqrawi et al., 2006). Based on the petrographic analysis of available samples, several types of dolomites or dolomitization phases are recognized including fabric-retentive, fabric destructive and saddle (Fig. 9).
- **Fabric retentive dolomitization**
  This dolomitization phase is recognized as small crystals (>16 µm) which finely replaced all parts of the precursor limy facies (both allochems and micritic matrix; Figs. 9A and 9B). This phase is reported from all parts of the studied section of the Asmari Formation (Fig. 3).
- **Fabric destructive dolomitization**
  The fabric destructive dolomitization is destroyed allochems and sedimentary texture via replacement by dolomite rhombs (62-100 µm; Figs. 9C to 9F). It led to crystalline texture of the studied samples which differs from partial to wholly replacement (Figs. 9E and 9F) which usually postdated most of the recognized diagenetic features such as calcite cementation and followed by later anhydrite cementation. This type of dolomitization is visible in the uppermost, lowermost and middle part of the Asmari Formation (Fig. 3).
  Following downward percolation of hypersaline fluids thorough the formerly deposited carbonate sediments (seepage-reflux model; Saller & Henderson, 1998; Melim & Scholle, 2002) there is a spectrum of dolomitization intensity from fabric retentive to fabric destructive types with decreasing Mg/Ca ratio (Error! Reference source not found.).
- **Saddle dolomite**
  Saddle dolomite is recognized as replacive and fracture-filling coarse crystals (>100 µm) with typical curved cleavages and undulose extinction (Figs. 9G and 9H). The saddle dolomites are recognized in the upper and lowermost parts of the Asmari Formation (Fig. 3).
  Saddle dolomites show burial realm and oil-window with temperatures of 100 to 150 °C (Esteban & Taberner, 2003; Machel, 2005).

**Fracturing**
Fractures in the studied Asmari Formation are classified into open and filled. They are filled by calcite, anhydrite and saddle dolomite (Figs. 4A, 5D, 8B and 9H). Open fractures are visible in the upper part of the studied section (Fig. 3). Fractures are recorded in both limestones and dolostones and all microfacies.

Some evidence such as their development in dolomitic intervals (Fig. 8B) and blocky calcite and saddle dolomite fillings confirms their development during the burial.

**Diagenetic realms and paragenesis**
Based on the detected diagenetic features during the petrographic analysis of the Asmari Formation, four diagenetic realms were differentiated as follows:
- **Marine diagenesis**
  Just after deposition in marine sedimentary environments, carbonate sequences were undergone diagenetic modifications. Marine cementation is typical of high energy shoal? facies in form of isopachous cements surrounded allochems. In such high energy environment, continuous charging of sea water into the pore spaces of sediments (high water to rock ratio) caused chemical precipitation of CaCO3 as isopachous cements. Intense marine cementation of carbonate sediments can provide a rigid framework against the subsequent diagenetic modifications, especially mechanical and chemical compaction. However, due to low frequency of typical shoal facies and later diagenetic overprints in the studied successions, it is not frequent.
- **Meteoric diagenesis**
  The presence of filled molds (Fig. 8A) and vuggy pores through the Asmari interval and also some calcite cement types such as drusy and equant calcite cements, indicate effects of meteoric diagenesis realm. Rather than meteoric dissolution and consequent cementation, mineral stabilization and replacement by equant and drusy and later blocky (burial) calcite cements is other alteration of this stage (Figs. 7C and 7D). The dissolution of meta- to unstable (aragonitic) grains, commonly bivalves and (small) benthic foraminifera (Fig. 8C), has resulted in fabric selective pore spaces (moldic and, to some extent, vuggy) in the studied formation. Therefore, this process must be considered as early diagenetic features that have affected carbonate sequences before their consolidation in burial realms.
- **Hypersaline/shallow burial diagenesis**
  Hypersaline diagenesis is one of the most important
and effective diagenetic stages, which have had considerable impacts on the history of reservoir evolution of the Asmari carbonates and also other dolomitic reservoirs (e.g. Aqrawi et al., 2006).

In dolomitic parts of the studied intervals, dolomitization phases occurred as fabric retentive and fabric destructive.

In general, after precipitation of evaporites in the nearby supratidal setting or evaporation in the restricted parts of the lagoon, remaining fluids are supersaturated relative to Mg and Ca, and then percolated through formerly deposited limy and mud- to grain dominated sediments—with interparticle porosity and flow potential—in both basin- and down-ward directions. This phenomenon has occurred just after deposition of carbonate mud in intertidal and subtidal settings (Chafetz et al., 1999; Warren, 2000; Meyer, 2005).

Following downward percolation of hypersaline fluids thorough the formerly deposited carbonate sediments (seepage-reflux model; Saller & Henderson, 1998; Melim & Scholle, 2002) there is a spectrum of dolomitization intensity from fabric retentive to fabric destructive types with decreasing Mg/Ca ratio. Moreover, pore-filling and replacive anhydrite cementation has a close relationship with these hypersaline related dolomites which led to plugging of pores (Saller & Henderson, 1998).

- Burial diagenesis

After experiencing marine, meteoric and hypersaline, the studied Oligocene-Miocene succession has undergone shallow to deep burial diagenesis. Under high temperature - pressure condition of burial realm, several diagenetic alterations have affected the studied interval. Several diagenetic processes are detected as follows: syntaxial calcite overgrowth, blocky calcite cementation, compaction, neomorphism, saddle dolomite and fracturing. The latest phase of dolomitization in the Asmari Formations is saddle dolomite which has a correlation by the minimum required depth of 500 m and temperature of > 30 °C for chemical compaction (Machel, 1999; Duggan et al., 2001).

The occurrence order (relative timing) of diagenetic processes was acquired by studying of their textural relationships in petrographic studies. The paragenesis of detected diagenetic features is presented in Fig. 10 for the targeted intervals of the Field. In these successions, all diagenetic processes are arranged based on their occurrence time relative to their subsequent alterations. Among these phases, only some processes such as dissolution, dolomitization, and later fracturing had potential to create reservoir quality.

Sequence Stratigraphy

A comprehensive Asmari succession sequence stratigraphy has been investigated in both outcrop and well in different places in SW Iran. For example, van Buchem et al., (2010) based on isotope data, have distinguished three 3rd order sequences of Oligocene (Rupelian, early Chattian and late Chattian in age) and three Miocene sequences (early Aquitanian, late Aquitanian and early Burdigalian in age), at Tang-e-Gurgudan outcrop section, in the Dezful and Izeh Zones. Also, three Miocene sequences identified in one well (Well #13) by van Buchem et al., (2010) in the Dezful depression (Fig 10).

To construct a sequence stratigraphic framework and determine the key surfaces, different data containing the results of facies studies, logs response and the appearance or abundance of fossils (e.g. the ratio of planktonic to benthic foraminifera) are used.
The sequence boundaries were characterized by remarkable facies changes in the depositional succession and special diagenetic imprints associated with sea-level falling stage.

Accordingly, three 3rd-order Miocene sequences are identified (Fig. 10): Sequences 4 and 5, related to Aquitanian (Early Miocene), both begun with low-stand sedimentary packages of subaqueous anhydrides (known as ‘Basal and Middle Anhydrite’) that were precipitated from the basin center when the basin became isolated from the Neo-Tethys Ocean, meanwhile, sequence 6 is related to the Late Miocene (Burdigalian).

Since Oligocene Asmari deposits (lower Asmari) did not develop in the studied field, the three Oligocene sequences introduced by van Buchem et al., (2010) have not been distinguished. Generally, the Middle Asmari includes two sequences, namely sequences 4 and 5. The Upper Asmari comprises one sequence (sequence 6), (Fig. 10). During highstand systems tracts, the Middle and Upper Asmari successions were in a closed sedimentary basin with high salinities, supplying appropriate conditions for dolomitization (Aqrawi & Wennberg, 2007). This can also observed by the existence of both anhydrite nodules and cements within dolomitized beds.

**Discussion**

**Depositional setting of the Asmari Fm.**

According to detailed petrographic analysis, 12 recognized microfacies (Table 1) are classified into five facies belts including tidal flat (MF1, MF2, MF3), lagoon (MF4, MF5, MF6 and MF7), barrier (inner ramp, MF8, MF9), middle ramp (MF10) and outer ramp (MF11, MF12) (Fig. 11; Table 1). The outer ramp is determined by marly limestone and planktonic foraminifera wackestone specially *Globigerina* spp. and *Detropa*.

![Figure 11](image-url)
The dominance of the mud-support microfacies and the absence of sedimentary structures formed in the presence of wave currents indicate that MF12 was formed in an outer ramp setting (under storm wave base, SWB). The middle ramp is mainly characterized by algal wackestone, but some boundstone facies including coralline boundstone and bioclastic grainstone belonging to the sea-ward shoal can be attributed to the middle ramp setting. The inner ramp deposit includes high energy grainstone barrier, open marine and restricted lagoon, intertidal and supratidal facies. The restricted lagoon was characterized by the absence of marine fauna and low frequency of common bioclasts and also lack of porcelaneous benthic foraminifera (Miliolids, Borealis), which indicate limited water recirculation and restricted environment condition. According to gradual facies transitions and lack of evidence of turbidite deposits, slump structures and debris, significant reef structures, pisoids, and oncoids, it is indicated that the Asmari Formation was deposited on a homoclinal ramp-type carbonate platform in the studied field (Burchette & Wright, 1992) from the Aquitanian to Burdigalian (i.e. Early Miocene).

Distribution of facies and their effects on reservoir quality

Interpretation of the result of facies analysis and their distribution in the studied wells indicated that moderate to good reservoir the high energy shoal facies (Table 2; MF9) have less abundance in the studied wells (Fig. 10, i.e. depth: 1620-1625 Well A; 1410-1430 Well C; 1845-1850 Well D). In the backward shoal, shallow and mostly low-energy lagoon setting has established, in which various benthic organisms have developed with low biodiversity (Wilson, 1975; Buxton & Pedley, 1989; Flügel, 2004). These types of facies constitute a major part of the Asmari Formation in the studied field (Fig. 10, most extension is related to lagoonal facies with bad reservoir quality i.e. MF4, 5) (Table 2), in which their reservoir quality is enhanced through moldic and vuggy dissolution and intragranular porosities (Fig. 7-C and D) (Table 2). Their poro-perm data suggest their diagensis was possibly facies-dependent.

An increase in energy of the carbonate platform, which leads to the cleanliness of the matrix and the formation of grain-dominated facies (MF7, MF8, and MF9) (Figs. 3 and 10 and Table 2), is among the factors contributing to the formation of better reservoir facies (Fig 12: MF6 and Fig. 13: MF7, MF8) (Table 2). However, these facies are less found in the studied interval of Asmari Formation or limited to specific units (Figs. 3 and 10). The results obtained from facies analysis indicate that the middle part of the Asmari Formation is mainly consists of outer and middle ramp facies (sequence 4 and 5), whereas the upper Asmari Formation (sequence 6) is deposited on a relatively high-energy platform (the presence of the middle/inner ramp facies), and shows shoaling-upward cycles towards the evaporitic Gachsaran Formation (Fig. 10). Eventually, it is concluded that MF3 (intertidal), MF 6 and 7 (lagoon), MF 8 (back shoal), MF9 (shoal) and MF12 (basin) have good reservoir quality (Table 2, Figs. 12 and 13). There reservoir quality are originated from the depositional characteristics of the facies. In other words, the main controlling factor on their reservoir quality was depositional characteristics and/or a facies-dependent diagenesis.

<table>
<thead>
<tr>
<th>Microfacies</th>
<th>Depositional Environment</th>
<th>Porosity (Fraction)</th>
<th>Permeability (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>MF1</td>
<td>Supratidal</td>
<td>0.002</td>
<td>0.100</td>
</tr>
<tr>
<td>MF2</td>
<td>Supratidal to intertidal</td>
<td>0.020</td>
<td>0.150</td>
</tr>
<tr>
<td>MF3</td>
<td>Intertidal</td>
<td>0.080</td>
<td>0.290</td>
</tr>
<tr>
<td>MF4</td>
<td>Lagoon</td>
<td>0.012</td>
<td>0.250</td>
</tr>
<tr>
<td>MF5</td>
<td>Lagoon</td>
<td>0.025</td>
<td>0.120</td>
</tr>
<tr>
<td>MF6</td>
<td>Restricted lagoon</td>
<td>0.010</td>
<td>0.280</td>
</tr>
<tr>
<td>MF7</td>
<td>Lagoon</td>
<td>0.120</td>
<td>0.220</td>
</tr>
<tr>
<td>MF8</td>
<td>Back shoal</td>
<td>0.015</td>
<td>0.200</td>
</tr>
<tr>
<td>MF9</td>
<td>Shoal (inner ramp)</td>
<td>0.020</td>
<td>0.200</td>
</tr>
<tr>
<td>MF10</td>
<td>Middle ramp</td>
<td>0.017</td>
<td>0.100</td>
</tr>
<tr>
<td>MF11</td>
<td>Open marine</td>
<td>0.060</td>
<td>0.120</td>
</tr>
<tr>
<td>MF12</td>
<td>Outer ramp/ basin</td>
<td>0.010</td>
<td>0.180</td>
</tr>
</tbody>
</table>
Linking diagenesis to the facies types and their controls on reservoir quality

Diagenetic processes including cementation, dissolution and dolomitization as well as features have resulted in different reservoir quality of the same facies in the studied wells (Fig. 14 well B and C; Fig. 15). Dolomitization and other digenesis processes, i.e., dissolution and fracturing have affected the Asmari Formation, that led to the generation of porosity and permeability and development of reservoir characters system (Fig. 14 and Figs. 15-B, C and D), especially in Lagoon microfacies which have been dolomitized (Fig. 7-C and Fig. 8) (Table 2). However, permeability at the
uppermost interval of the Upper Asmari is decreased due to fracture filling anhydrite cement (Fig. 3, Fig. 7-A, B and Fig. 15-A). Compaction and cementation (Anhydrite and Calcite) have had negative effects on reservoir quality (Fig. 14, Fig. 15-A and Fig. 6-D, E). Anhydrite and calcite cements mostly filled both pore spaces and fractures and therefore have decreased reservoir quality (Fig. 14 and Fig. 15-A).

Dolomitization through evaporate brines (Fig. 9) is another cause for improving porosity and permeability in mud-dominated intertidal to lagoonal facies (MF3, MF5 and MF6; Table 2) (Figs. 12, Fig. 13 and Fig. 15-D).

Figure 13. Porosity versus permeability on the Lucia rock fabric class Lucia, (2007) for the identified MF7 to MF12.
Figure 14. Illustrate the effect of diagenetic processes on porosity and permeability of the Asmari reservoir in the studied field.

However, the permeability values are generally less than 10 MD due to the fine-sized crystals of dolomites (Fig. 8-A, B) or the fracture-filling anhydrite cements (Fig. 7-A, B and Figs. 12 and 13). Next to the fracturing, dolomitization processes had main constructive effect on the reservoir quality of the studied reservoir (Fig. 14 and Fig. 15-D). Dissolution, as one of the major
causes of porosity enhancement (especially in the upper part of HST), is mainly developed in benthic foraminifera wacke/pack to grainstone facies (MF6 and MF8) (Fig. 3 and Fig. 7-C), which have less abundance in the studied field (Fig. 14 and Fig. 15-B). The high porosity values of MF6 and MF7 are mainly resulted from the development of vuggy porosities and intercrystalline porosity (Figs. 12, 13 and Fig. 15-B). Compaction features (both mechanical and stylolite forms) have negative impact in mud-dominated facies (i.e., MF6 and MF11) (Fig. 7-D, E and Fig. 14). Therefore, two major factors of primary depositional environment (mineralogical composition and initial texture) and development of vuggy and intercrystalline porosities (Fig. 15-B) along with fracturing (Fig. 15-C) and dolomitization (Fig. 15-D) processes have made reservoir potential.

Linking reservoir quality to the sequence stratigraphy

Interpretation of the results of sequence stratigraphy and its comparison with the facies distribution as well as reservoir quality indicates a relatively direct relationship between reservoir parameters and identified system tracts. Overall, TST, is composed of lagoonal (restricted/open marine lagoon) facies (MF1, MF4, MF5, MF6 and MF7), whereas, HST consists of bioclastic grainstone (MF8) and coral boundstone facies (MF9) of the inner ramp. Due to the presence of benthic foraminifera pack to grainstone and coral boundstone as well as inter/intra-particle porosities from dolomitization and dissolution of the unstable aragonite components (e.g., *Borelis* fossil, Fig. 6-C) in these facies in the HST, on the one hand, and the dominance of mud-supported facies with limy micrite and calcite/anhydrite cements in the TST, on the other hand, reservoir quality of the HST is higher than the TST (Figs. 16 and 17) (Table 3).

Figure 16. Porosity-permeability cross-plot of the introduced sequence and systems tract of the Asmari Formation representing high reservoir quality of HST than TST resulted from dolomitization, fracturing and dissolution.
Table 3. Main petrophysical property of the identified sequence and systems tract for the Asmari succession in the studied oil field.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Systems Tact</th>
<th>Porosity</th>
<th>Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seq. 6</td>
<td>HST</td>
<td>0.015</td>
<td>0.200</td>
</tr>
<tr>
<td></td>
<td>TST</td>
<td>0.01</td>
<td>0.20</td>
</tr>
<tr>
<td>Seq. 5</td>
<td>HST</td>
<td>0.01</td>
<td>0.180</td>
</tr>
<tr>
<td></td>
<td>TST</td>
<td>0.015</td>
<td>0.180</td>
</tr>
<tr>
<td>Seq. 4</td>
<td>HST</td>
<td>0.010</td>
<td>0.170</td>
</tr>
<tr>
<td></td>
<td>TST</td>
<td>0.013</td>
<td>0.080</td>
</tr>
</tbody>
</table>

Figure 17. Reservoir quality distribution in the upper part of the Asmari Formation (Sequence 6); the values of the porosity and permeability increase towards the sequence boundary.

From maximum flooding surface towards the sequence boundary (Fig. 17), reservoir quality has been improved through the creation of vuggy porosities (resulted from meteoric dissolution, Fig. 7-C) and intercrystalline porosities (resulted from dolomitization, Fig. 8-E). In contrast, the reservoir quality has been decreased towards the MFS because of the presence of mud-supported facies of the distal middle ramp and outer ramp (Fig. 17). The sequence 4 has the worst reservoir quality in the studied wells, particularly in well B, in which cementation (mostly anhydrite cement) resulted in decreasing porosity and permeability (Fig. 16 and Table 3).

The upper sequence of Asmari (sequence 6) is composed of the wide-range facies (outer ramp to
barrier facies in TST and lagoonal to supratidal facies in HST part) in the observed wells, which is indicative of a relatively constant eustacy at the Burdigalian stage. This sequence shows better reservoir quality than the middle Asmari (sequences 4 and 5) (Fig. 16), due to the high frequency of high quality reservoir facies (MF3, 6, 7 and 8) along with the influence of constructive diagenetic features such as dissolution and dolomitization (Fig. 3, Figs 15-B and D) (Table 3). Overall, reservoir quality from sequence 4 toward sequence 6 due to increases in dolomitization, more dissolution along with stability of the basin resulted in constant increases in sea level in Burdigalian (it is concluded from the high thickness of the sequence and more uniformity/similarity of the facies) is increased (Fig. 3, Fig. 15 and Fig. 16) (Table 3).

Conclusions
Based on petrographic observation, 12 microfacies belonging to a homoclinal ramp-type system have been identified. These facies were classified into five sub-environment including tidal flat, lagoon, barrier, middle ramp, and outer ramp. Tidal flat, lagoonal and barrier microfacies mostly present in the upper and some middle parts of the Asmari reservoir, while middle and outer ramp microfacies largely developed in the middle part. Results of depositional environment study indicate that an inner and middle part of a homoclinal ramp dominated during the deposition of the Asmari succession in the studied field. Intertidal (MF3), lagoon (MF 6 and 7), back shoal (MF 8), and basin (MF12) have good reservoir quality, that indicated reservoir quality are originated from the depositional characteristics of the facies. In other words, the main controlling factor on their reservoir quality was depositional characteristics and/or a facies-dependent diagenesis.

The major diagenetic processes affecting the Asmari succession include compaction, cementation, dolomitization, dissolution, and fracturing. Whereas dissolution, dolomitization, and fracturing are contributed to porosity and permeability enhancement, cementation and compaction have reduced the reservoir quality. Intercrystalline pore spaces created from dolomitization (especially fabric retentive dolomitization in inner ramp facies), molds and vuggy pore space resulted from dissolution are the most important diagenetic pore type that has affected the reservoir quality.

From the sequence stratigraphic perspective, the Lower Asmari has not been recorded in the studied oil-field. Three 3rd-order Miocene sequences are distinguished on the basis of deepening and shallowing trends of facies. Sequence 6 has the best reservoir quality in the studied oil-field. Highstand systems tract in this sequence has better reservoir quality than transgressive system tract because of the dolomitization, fracturing, and dissolution.

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