DOLOMITIZATION AND RELATED FLUID EVOLUTION IN THE OLIGOCENE – MIOCENE ASMARI FORMATION, GACHSARAN AREA, SW IRAN: PETROGRAPHIC AND ISOTOPIC EVIDENCE

I. S. Al-Aasm*, F. Ghazban** and M. Ranjbaran+

Petrographic and stable isotope investigations of Oligocene-Miocene carbonates in the Asmari Formation from the Gachsaran oilfield and surrounding area in SW Iran indicate that the carbonates have been subjected to extensive diagenesis including calcite cementation and dolomitization. Diagenetic modification occurred in different diagenetic realms ranging from marine, meteoric and finally burial.

Asmari carbonates were in general deposited in a ramp setting and are represented by intertidal to subtidal deposits together with lagoonal, shoal and low-energy deposits formed below normal wave base. Lithofacies include bioclastic grainstones, ooidal and bioclastic, foraminiferal and intraclastic packstones, and mudstones. Multiple episodes of calcite cementation, dolomitization and fracturing have affected these rocks to varying degrees and control porosity. Four types of dolomites have been identified: microcrystalline matrix replacement dolomite (D1); fine to medium crystalline matrix replacement dolomite (D2); coarse crystalline saddle-like dolomite cement (D3); and coarse crystalline zoned dolomite cement (D4).

Microcrystalline dolomites (D1) (6-12 μm) replacing micrite, allochems and calcite cements in the mud-supported facies prior to early compaction show δ18O and δ13C values of -4.01 to +1.02 ‰ VPDB and -0.30 to +4.08 ‰ VPDB, respectively. These values are slightly depleted with respect to postulated Oligocene-Miocene marine carbonate values, suggesting their precipitation from seawater, partly altered by later fluids. The association of this type of dolomite with primary anhydrite in intertidal facies supports dolomitization by evaporative brines.

Fine to medium crystalline matrix dolomites (D2) (20-60 μm) occur mostly in grainstone facies and have relatively high porosities. These dolomites formed during early burial and could be considered as recrystallized forms of D1 dolomite. Their isotopic values overlap those of D1 dolomites, implying precipitation from similar early fluids, possibly altered by meteoric fluids.

Coarse crystalline saddle-like dolomites (D3) (200-300 μm) partially or completely occlude fractures and vugs. The vugs developed through the dissolution of carbonate components and rarely matrix carbonates, while fractures developed during Zagros folding in late Oligocene to early Miocene times.

A final diagenetic episode is represented by the precipitation of coarse crystalline planar e-s zoned dolomite (D4) (80-250 μm) that occurs in fractures and vugs and also replaces earlier dolomite and post-dates stylolitization. Fluids responsible for the formation of D3 and D4 dolomites are affected by brine enrichment and increasing temperatures due to increasing burial.

Key words: Dolomites, diagenesis, Oligocene-Miocene, Asmari Formation, Gachsaran, Iran, pore fluids, carbonates, geochemistry

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Reservoir porosity is dominated by microcrystalline pore spaces in muddy, dolomitized matrix and mouldic and vuggy porosity in grainstone. Porosity was significantly enhanced by the formation of multiple fracture systems.

INTRODUCTION

The Oligocene - Lower Miocene Asmari Formation and its time-equivalents form one of the world’s most important petroleum reservoirs which is estimated to contain more than 90% of the recoverable hydrocarbons of Iran and Iraq (Beydoun et al., 1992; Ghazban, 2007). These carbonates have been the subject of detailed study ever since the first petroleum reservoir was discovered at Masjid-e Suleiman in SW Iran in 1908 (e.g. Busk and Mayo, 1918; Adams, 1969; Wells, 1967). Lees (1933) was the first to carry out a systematic investigation of the Asmari Formation. Biostratigraphic and microfacies analyses include studies by James and Wynd (1965); Kalantari (1986); Seyrafin and Hamedani (1998); Seyrafin (2000); Nadjafi et al. (2004); Vaziri-Moghaddam et al. (2006) and Ranjbaran et al. (2007). Fracturing is of vital importance for oil production (James and Wynd, 1965; McQuillan, 1973, 1985; Gholipur, 1994, Nemati and Pezheshk, 2005).

Recent studies have considered diagenetic features of the Asmari Formation including dolomitization and porosity modification (Aqrawi et al., 2006; Ehrenberg et al., 2007; Ranjbaran et al., 2007). In this paper, we report on dolomitization of the formation and its effect on reservoir characteristics in the Gachsaran area of SW Iran. The Gachsaran oilfield, an anticlinal structure 80 km long and 8-18 km wide, was discovered in 1928 and has more than 320 producing wells. We discuss the occurrence, distribution and timing of diagenetic phases affecting the Asmari Formation in the study area, deduce the possible source and chemical composition of basinal fluids, and propose a model to account for the distribution of dolomites and for their influence on the evolution of reservoir porosity.

Regional geology

The Oligocene – lower Miocene Asmari Formation platform carbonates were laid down on the margins of the evolving foreland basin which resulted from the convergence of the NE Arabian Plate and Iranian blocks (Stocklin, 1968; Sherkati and Letouzey, 2004; Alavi, 2004; Ghazban, 2007) (Fig. 1). Foreland basin subsidence began in the Late Cretaceous and in Lurestan the depocentre migrated progressively to the SW (Farzipour-Saein et al., 2009). By the Oligocene, prograding carbonate platforms (Asmari Formation) surrounded a deep-water, NW-SE trending basin in which the shales and limestones of the Eocene Pabdeh Formation had been deposited (James and Wynd, 1965; Motiei, 1993; Aqrawi et al.,
The Asmari carbonates prograded over the Pabdeh shales and the Asmari-Pabdeh contact is diachronous, becoming younger basinward (Thomas, 1952).

A significant pulse of siliciclastics entered the Asmari basin from the west in the early Miocene resulting in deposition of the Ahwaz Sandstone. The unit is restricted to the SW margin of the basin (Alavi, 2004; Jafarzadeh and Hosseini-Barazi, 2008) (Fig. 1) and is interpreted to have been deposited in a range of paralic, deltaic (possibly aeolian) depositional environments (Motiei, 1993). The evaporitic Kalhur Anhydrite is confined to a narrow sub-basin in the north of the Dezful Embayment (Motiei, 1993).

The transition from the Asmari carbonates to the overlying Gachsaran evaporites records restriction and desiccation of the basin (Koop and Stoneley, 1982; Stoneley, 1990; Ghazban, 2007). In southern Iran and the Persian Gulf, these evaporites serve as effective seals for hydrocarbons generated within underlying Cretaceous source rocks which migrated upwards through faults and fractures into the Asmari reservoirs (Motiei, 1993; Ghazban, 2007).

**Stratigraphy and depositional environment**

The Asmari Formation at its type locality in the Asmari Mountains (James and Wynd, 1965) consists of 314 m of interbedded limestones and shales (Fig. 2) which in general thin to the SE (Fig. 3). The Ahwaz Sandstone has a thickness of 213 m at the type section but is thicker at Gachsaran. The Asmari Formation consists of medium- to thick-bedded, skeletal or oolitic, nummulite-bearing limestones (grainstone, packstone, wackestone), which shoal upwards above a thin basal conglomerate from fine-grained (low-energy) deep-marine marly limestones to high-energy shallow-marine skeletal grainstones.

The Asmari limestone overlies deep-water shales and marls of the Pabdeh Formation in the SW of the Zagros basin. The lower part of the Asmari Formation interfingers with the Pabdeh Formation in the Dezful Embayment (Motiei, 1993), while the upper part covers nearly the entire Zagros Basin. To the north of the Dezful Embayment, the Asmari Formation is unconformably overlain by the Gachsaran evaporites.

The Asmari Formation can be divided into lower, middle and upper parts. The basal third (Lower Asmari) consists of calcareous sandstones and sandy limestones with minor shales (i.e. the Ahwaz Member of James and Wynd, 1965). At the base are marls overlain by foraminiferal and coralline algal limestones dated by Eames et al. (1962) as Rupelian-Chattian. The Middle Asmari comprises dolomitized, lagoonal limestones, while the Upper Asmari is evaporitic.

Lower Asmari strata are interpreted to have been deposited under relatively open-marine, high-energy conditions while middle to upper Asmari strata were deposited in relatively restricted, evaporitic conditions. These changes are indicated by the prevailing depositional facies and also from the abundance of dolomite and anhydrite (Ehrenberg et al., 2007).

Detailed field and petrographic investigations of the Asmari Formation have resulted in the recognition

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**Fig. 2. Stratigraphy of the Asmari Formation at its type section (modified from Mossadegh et al., 2009).**
of depositional facies including arid tidal-flat, back barrier lagoon, barrier (reef/grainstone), and shallow- and deep-water open-marine (pelagic and calciturbidite facies) belts (Table 1; Fig. 4). In general, the depositional environment can be interpreted as a shallow homoclinal carbonate ramp with a gentle slope which evolved to a middle and finally an outer ramp (e.g. Nadjafi et al., 2004; Ranjbaran et al., 2007).

**SAMPLING AND ANALYTICAL METHODS**

A total of 362 samples of the Asmari Formation carbonates were collected for petrographic and other analyses. Surface samples were collected from the Jahad Abad, Kuh-e Pahan and Muj village localities (Fig. 1); subsurface samples came from three wells in the Gachsaran oilfield (GS-25, 31 and 37). Thin sections were examined under a standard petrographic microscope and stained with a mixture of Alizarin Red S and potassium ferricyanide (Dickson, 1965). Cathodoluminescence (CL) microscopy was carried out using a Technosyn cold cathodoluminescence stage with a 12–15 kV beam and a current intensity of 420–430 µA. Fluorescence characteristics were studied with a Nikon EPI Ultraviolet Fluorescence lamp connected to a petrographic microscope. Selected samples were examined under SEM to investigate microporosity and dolomite types. Where precursor fabrics had been destroyed by pervasive dolomite replacement, the white card technique (e.g. Folk, 1987), diffused plane-polarized light (Dravis, 1991) or fluorescence microscopy (Dravis and Yurewicz, 1985) was utilized.

Various generations of calcite cements together with fossil components, dolomite and carbonate matrix were microsampled for stable oxygen and carbon isotope analysis using a microscope-mounted drill assembly to extract the desired quantity (2 to 5 mg for isotope analysis) of powdered samples from polished slabs. The samples for isotope analysis (n=56) were reacted in a vacuum with 100% pure phosphoric acid for at least 4 h at 25°C for calcite and 50°C for dolomite using the method described by Al-Aasm et al. (1990). The evolved CO$_2$ gas was analyzed for carbon and oxygen isotopic ratios on a Delta plus mass spectrometer at the University of Windsor, Canada. Values of stable oxygen and carbon isotopes are reported in per mil (‰) notation relative to the Peedee Belemnite (VPDB) standard and were corrected for phosphoric acid fractionation. Precision was better than 0.05‰ for both $\delta^{18}$O and $\delta^{13}$C.

**DIAGENESIS**

Diagenetic modification of the Asmari Formation carbonates in the Gachsaran area includes multiple episodes of calcite cementation, dolomitization, mechanical and chemical compaction, minor secondary anhydritization, calcitization, fracturing and dissolution (Fig. 5). Major diagenetic features are discussed below with particular emphasis on dolomitization.

**Calcite Cementation**

Calcite cementation was of limited significance in the studied thin sections. Four types of mainly non-ferroan calcite cements were observed, from early to late stage (Table 2): (1) bladed, prismatic isopachous rim calcite (C1; Fig.6A); (2) syntaxial overgrowth...
Fig. 4. Photomicrographs illustrating the main lithofacies types in the Asmari Formation.

A. Planktonic foraminiferal wackestone-packstone.
B. Nummulitic-bioclastic wackestone-packstone.
C. Bioclastic grainstone.
D. Ooid grainstone; ooids are cross-cut by late calcite veins.
E. Bioclastic miliolid-borelisid wackestone-packstone.
F. Miliolid packstone.
G. Mudstone containing silty fine-grained detrital quartz.

A, B, C and D: outcrop samples from the Jahad Abad locality.
E: outcrop sample from the Muj village locality.
F and G: outcrop samples from the Kuh-e-Pahan locality.

Table 1. Lithofacies types and depositional environments of the Asmari Formation.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Characteristics</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planktonic foraminifer wackestone-packstone</td>
<td>Predominant skeletal grains are planktonic foraminifera</td>
<td>Low energy, deposition below normal wave base</td>
</tr>
<tr>
<td>Nummulitic-bioclastic-coralinacean wackestone-packstone</td>
<td>Skeletal grains consist of benthic foraminifera, coralinacean, fragments of echinoderms and bryozoans. The benthic foraminifera include large Lepidocyclina, Miogypsinids and Amphistegina. Rare planktonic foraminifera are also present.</td>
<td>Middle ramp, near high energy shoal</td>
</tr>
<tr>
<td>Bioclastic grainstone</td>
<td>High abundance of shell fragments (mainly mollusc debris). Bioclasts show micritic envelopes. Subordinate biota includes benthic foraminifers (Operculina and Lepidocyclina)</td>
<td>Shoal setting above normal wave base; perhaps platform margin</td>
</tr>
<tr>
<td>Ooid-grainstone</td>
<td>Ooid grainstones are relatively rare and are characterized by grain-supported textures in which the principle allochems are ooids (often only superficially coated grains) and peloids</td>
<td>Inner ramp, back shoal setting</td>
</tr>
<tr>
<td>Bioclastic-miliolid-borelisid wackestone-packstone</td>
<td>Benthic foraminifera, borelisids, and miliolids. Other components are echinoderm fragments and coralline algae</td>
<td>Shelf lagoon environment</td>
</tr>
<tr>
<td>Miliolid-intraclast-bioclastic wackestone-packstone</td>
<td>Benthic foraminifers (miliolids), bioclasts (fragments of echinoderms and mollusc shells) and more or less rounded intraclasts</td>
<td>Restricted lagoon with a nearby tidal flat</td>
</tr>
<tr>
<td>Carbonate mudstones</td>
<td>Silt to very fine-grained sand-sized detrital quartz grains. Bioclasts are restricted to rare ostracode and phosphatic debris. In some instances the mudstones are distinctly laminated, while in others extensively bioturbated. Several sub-facies can be recognized based on degree of bioturbation and bioclastic debris</td>
<td>Intertidal to subtidal setting</td>
</tr>
</tbody>
</table>
### Paragenetic Sequence for the Asmari Formation Carbonates

**Diagenetic Settings and Their Relative Timing**

<table>
<thead>
<tr>
<th>Early Process</th>
<th>Mid-Burial Process</th>
<th>Late Process</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deposition</strong></td>
<td><strong>Calcite Cementation</strong></td>
<td><strong>Dolomitization</strong></td>
</tr>
<tr>
<td><strong>Processes</strong></td>
<td>Calcite 1, Calcite 2, Calcite 3, Calcite 4</td>
<td>Dolomite 1, Dolomite 2, Dolomite 3, Dolomite 4</td>
</tr>
<tr>
<td><strong>Chemical Compaction</strong></td>
<td><strong>Anhydritization</strong></td>
<td><strong>Dissolution</strong></td>
</tr>
<tr>
<td><strong>Mechanical Fracturing</strong></td>
<td><strong>Calcitization</strong></td>
<td><strong>Oil Emplacement</strong></td>
</tr>
</tbody>
</table>

*Fig. 5. Paragenetic sequence for the Asmari Formation carbonates. Diagenetic settings and their relative timing are based on petrographic and geochemical relationships.*

Rim calcite (C2; Fig. 6B); (3) equant calcite (C3, Flg. 6C); and (4) blocky calcite cement (C4).

Based on their morphologies the first two generations of cement (C1 and C2) are interpreted to have formed during early diagenesis in a marine phreatic environment, while the latter types of calcite cements formed during shallow to deeper burial stages. Bladed, prismatic isopachous rim cement (C1) surrounds ooids and peloids in the grainstone facies. In this facies, syntaxial, inclusion-free overgrowth cements (C2) occur on crinoid fragments. Some of these calcite cements are partially replaced by dolomite and secondary anhydrite. C3 and C4 calcite cements are abundant and occur mostly as equant, drusy fabric occluding vugs and fractures.

**Anhydritization**

Two generations of anhydrite are present within the Asmari carbonates (Table 2): primary and secondary. Primary anhydrite in general has a nodular chicken-wire texture and is locally present in the middle and upper parts of the formation. Nodules of anhydrite occur in a variety of carbonate lithologies from mudstones, wackestones to packstones and grainstones. Secondary diagenetic anhydrite is more widespread compared to the primary anhydrite, and occurs both as nodules and vug- and fracture-filling calcite cements.

*Fig. 6. Photo-micrographs showing types of calcite cementation in the Asmari Formation. Samples from outcrop localities.*

- A. Isopachous rim cement surrounding coated grains, followed by equant calcite cement occluding the remaining porosity.
- B. Syntaxial rim cementation over crinoidal fragment.
- C. Late equant calcite cement (x) filling a fracture.
cements (up to 1 mm). Nodules are usually distributed along fracture planes.

**Dolomitization**

Dolomitization is the most important control on porosity and permeability development in the Asmari Formation after fracturing. Dolomitization is widespread, occurring particularly in the middle and upper parts of outcrop successions. In the subsurface, dolomitization preferentially affected oolitic grainstones and mudstones, and the resulting textures and mineralogies vary from limestones to sucrosic dolostones, partially dolomitic limestones and calcitized dolostones.

Dolomite characteristics such as crystal shape and size, presence of fluid inclusions and timing relative to other diagenetic features (e.g. compaction and stylolite formation) were carefully recorded. Based on staining and detailed petrographic examinations, four types of dolomite have been recognized (textural classification follows Sibley, 1982; and Sibley and Gregg, 1987):

1. early replacive microdolomite;
2. fine to medium crystalline matrix dolomite;
3. saddle-like dolomite cement; and
4. replacive and cement-cloudy centre-clear, coarse crystalline dolomites.

The first two types of dolomite are the most common. Early replacive microdolomite (D1, Figs. 7A, B, 8A; Table 2) is characterized by very fine crystal size and texture (6-12 μm in size). Crystals are euhedral and show non-luminescent CL characteristics. Dolomite crystals with a non-ferroan, planar-e fabric replace algal mud matrix and are also associated with burrowed, mottled, fenestral carbonates and are intercalated with primary, nodular anhydrite.

Dolomite characteristics such as crystal shape and size, presence of fluid inclusions and timing relative to other diagenetic features (e.g. compaction and stylolite formation) were carefully recorded. Based on staining and detailed petrographic examinations, four types of dolomite have been recognized (textural classification follows Sibley, 1982; and Sibley and Gregg, 1987):

<table>
<thead>
<tr>
<th>Phase</th>
<th>Texture</th>
<th>Crystal Shape</th>
<th>Crystal size (μm)</th>
<th>CL</th>
<th>Other features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcite 1</td>
<td>Isopachous rim</td>
<td>Bladed-prismatic</td>
<td>&lt;20-30</td>
<td>non</td>
<td>Surrounds ooids and peloids</td>
</tr>
<tr>
<td>Calcite 2</td>
<td>Syntaxial</td>
<td>vary</td>
<td></td>
<td>non</td>
<td>Inclusion-free surround crinoids</td>
</tr>
<tr>
<td>Calcite 3</td>
<td>Blocky</td>
<td>Equant</td>
<td>&lt;100-200</td>
<td>Dull red</td>
<td>Non-ferroan, vug and fracture fill</td>
</tr>
<tr>
<td>Calcite 4</td>
<td>Drusy fabric</td>
<td>Equant</td>
<td>&gt;200</td>
<td>Dull red</td>
<td>Fracture-fill</td>
</tr>
<tr>
<td>Anhydrite 1</td>
<td>Chicken-wire and nodular</td>
<td></td>
<td>non</td>
<td>Primary deposit and occurs in mudstone and wackestone facies</td>
<td></td>
</tr>
<tr>
<td>Anhydrite 2</td>
<td>Nodular and replacement</td>
<td>Lath shaped</td>
<td>Up to 1 mm</td>
<td>Secondary replacement and vug-filling deposit</td>
<td></td>
</tr>
<tr>
<td>Dolomite 1</td>
<td>Microdolomite</td>
<td>Planar-e</td>
<td>6-12</td>
<td>non</td>
<td>Non-ferroan, co-exists with primary anhydrite in intertidal facies</td>
</tr>
<tr>
<td>Dolomite 2</td>
<td>Micro-medium crystalline matrix</td>
<td>Planar-s</td>
<td>20-60</td>
<td>Non to dull red</td>
<td>Occurs mostly in grainstone facies</td>
</tr>
<tr>
<td>Dolomite 3</td>
<td>Saddle-like dolomite</td>
<td>Undulose extinction</td>
<td>200-300</td>
<td>Dull red</td>
<td>Inclusion-rich cores and inclusion-free rims</td>
</tr>
<tr>
<td>Dolomite 4</td>
<td>Zoned dolomite</td>
<td>Planar-e to planar-s</td>
<td>80-250</td>
<td>Dull to bright red</td>
<td>Inclusion-rich cores</td>
</tr>
</tbody>
</table>

Table 2. Petrographic characteristics of the main diagenetic phases within the Asmari Formation.
replaces authigenic anhydrite. In general, saddle dolomite displays turbid inclusion-rich centres and clear, inclusion-poor rims. Under CL microscopy, saddle dolomites display a dull luminescent colour.

Zoned dolomites (D4; Table 2), are characterized by a crystal sizes of 80–250 μm and by a planar-e to planar-s fabric which shows an increase in non-planar crystal boundaries with increasing crystal size. It occurs both as replacive and as vug-rimming cement (Fig. 9C). Zoned dolomites have dark cores and lighter rims and post-date stylolite formation.

**Fracturing**

Three different types of fractures were observed in the study area and have a range of sizes, orientations and infilling cements. They are (Fig. 10): (1) microfractures, (2) mesofractures and (3) tension gashes.

Microfractures (ca.50 μm in width) probably represent a first generation of fractures (c.f. Ameen and Hailwood, 2008). Mesofractures have larger apertures and have variable orientations, cross-cutting earlier microfractures (Fig. 10B). Tension gashes are lenticular in shape and are filled with late calcite cement (Fig. 10A). Tensile fractures are contained by bedding planes, and are interpreted to have formed

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**Fig. 7. Photomicrographs illustrating dolomite types in the Asmari Formation.**
- A. Microcrystalline dolomite replacing matrix.
- B. Microcrystalline dolomite under SEM; note microporosity between dolomite rhombs.
- C. Medium crystalline replacive dolomite.
- D. Saddle-like dolomite cement (x).
- E. Dolomitized benthic foraminiferal wackestone showing non-selective dolomitization.
- F. Dolomitized miliolid grainstone.
- A, B, D and F: samples from outcrop localities; C and E: samples from core (well Gachsaran 37).

**Fig. 8. SEM photographs showing replacive and cement dolomites.**
- A. Microcrystalline dolomite; note intercrystalline porosity.
- B. Medium crystalline dolomite cement in a vuggy pore.
- C. Medium crystalline replacive dolomite.
Fractures can be oriented parallel or perpendicular to bedding and are often filled with cement (Fig. 10C). In massive parts of the Asmari Formation, vertically persistent fractures occur on length scales of hundreds of metres parallel to the axis of buckle folds.

Chemical compaction and dissolution fabrics

Three types of pressure dissolution features were identified: fitted fabrics, dissolution seams; and stylolites. Fitted fabrics are observed in grainstones, reflecting slightly sutured to curved to planar contacts between grain surfaces. Dissolution seams are observed in some wackestones and algal mudstones, while stylolites (Fig. 10D) occur in all lithofacies. Bed-parallel stylolites are frequently observed. Stylolites of tectonic origin (oblique or perpendicular to bedding planes) are less frequent (Ahmadhadi et al., 2008). Some skeletal fragments, presumably consisting of metastable carbonate minerals, were dissolved and then partly filled by calcite cement leading to the development of mouldic porosity. Partial dissolution of dolomite is also evident in some samples, where crystal boundaries show evidence of etching and creation of secondary porosity (Fig. 8C).

Calcitization

Calcitization was very rarely observed in a few samples. The intensity of calcitization varies from partially corroded dolomite crystals to complete dedolomitization (Fig. 9D). This process post-dates early and late dolomite formation and was associated with dissolution of precursor dolomite and the formation of secondary porosity.

RESERVOIR CHARACTERISTICS

Porosity in the Asmari Formation includes interparticle, intercrystalline, vuggy and fracture types; moulds and vugs are the main type of non-connected pore. Porosity is controlled by the diagenetic processes described above (dolomitization, calcite cementation, dissolution, fracturing and anhydritization).

Intercrystalline pores were observed in samples obtained from both surface and subsurface sections and range from 0.05 to 0.15 μm in diameter (Fig. 8A, B), and were studied under SEM (Fig. 9B). High volumes of intercrystalline pore space were observed in both original micrite and dolomite samples. Some intercrystalline pore spaces were enlarged by dissolution. Vuggy pore spaces include moulds, fractures, solution-enlarged fractures and fenestral pores (Fig. 10). Moulds formed through partial or complete dissolution of skeletal components.

In general, dolostones have higher porosity and permeability compared to limestones. Chilingar and Terry (1954) showed that there is a clear relationship between porosity and degree of dolomitization in the Asmari limestone, suggesting that dolomitization enhances porosity. This was confirmed by Lackpour et al. (2008).

Dolomitized successions are more susceptible to brittle fracturing than non-dolomititic units, and this has important implications for the location of the fracture networks which enhance production. The influence of mineralogical composition on petrophysical properties and fracture density has been investigated for the Asmari Formation by Nemati and Pezeshk (2005). They found that an increase in the...
dolomite content increases the maximum observed fracture density of the rocks in most lithology groups; however, no significant relationship was found between calcite content and fracture density.

Carbonate reservoir intervals in the Asmari Formation are characterized by low matrix porosity and permeability, and effective drainage is dependent on the occurrence of open fractures. McQuillan (1973) analyzed joint sets in Asmari carbonates in an intensely folded region and found that joint spacing is non-linearly related to layer thickness. He noted that joint intensity does not depend on local folding, and that fault-associated joints predominate in grabens. By contrast, Gholipour (1994) proposed that fractures in Asmari reservoirs are associated with the axial growth of concentric folds and are therefore mostly fold-related. At Kuh-e Pahn, axis-parallel fold-related fractures occur on the crest of the anticline and have a large vertical extent, primarily due to the lithological homogeneity of massive Asmari packstones (Stephenson et al., 2007).

**STABLE ISOTOPE GEOCHEMISTRY**

The stable isotopic compositions of some carbonate components in the Asmari Formation are presented in Table 3 and Figs 11 and 12. To avoid cross-contamination within different phases, only the following calcitic components were analyzed: fossils, micrite, equant calcite cement (C3) and fracture-fill calcite cement (C4). Of the various dolomite types, only fine crystalline dolomite (D1), medium crystalline dolomite (D2) and coarse crystalline dolomite (D4) were analyzed.

Calcitic fossils show δ¹⁸O and δ¹³C values ranging from -5.3 to +2.2‰ and -1.95 to +1.59 ‰ VPDB, respectively (Fig. 11); while micrite samples had δ¹⁸O and δ¹³C values of -7.61 to +1.43‰ and -0.92 to +2.84 ‰ VPDB (Fig. 12). The δ¹⁸O and δ¹³C of the non-ferroan equant calcite (C3) had values of -8.7 to -3.66‰, and -8.81 to +0.14‰ VPDB, respectively, while the non-ferroan blocky calcite cement (C4) showed δ¹⁸O and δ¹³C values of -9.55 to -2.77‰, and -2.29 to +1.51 ‰ VPDB, respectively (Fig. 12). C3 and C4 calcite show broad ranges in δ¹⁸O; however, fracture-filling coarse calcite spans a tighter range in δ¹³C than equant calcite. δ¹³C values are depleted in a few samples of equant calcite cement.

Selected skeletal and non-skeletal calcitic components (e.g. nummulites, molluscs and red algae) have comparable δ¹³C values to Oligocene-Miocene marine carbonates (cf. Veizer et al., 1999), while their δ¹⁸O values show negative shifts (Fig. 11). The range of δ¹⁸O values is larger than reported values for late Oligocene and early Miocene deep sea cores in which fluctuations are less than 1‰ (Zachos et al., 1997).

The δ¹³C and δ¹⁸O values of the equant and blocky calcite cements occluding vugs, fractures and other pore spaces show a clear co-variant trend mostly represented by equant calcite cement in vugs (r² =0.78), and a linear trend with high δ¹³C values corresponding to high δ¹⁸O values (Fig. 11).

The early replacive microdolomites (D1) show δ¹⁸O and δ¹³C values ranging from -2.42 to +1.02‰ and -0.31 to +4.08 ‰ VPDB, respectively (Fig. 12). The micro-mesodolomite (D2) shows δ¹⁸O and δ¹³C values of -2.21 to 1.22‰ and -0.08 to 3.71 ‰ VPDB. Coarse crystalline zoned dolomite (D4) shows δ¹⁸O
and $\delta^{13}C$ values of -0.02 to +0.99‰, and -0.6 to +2.22‰ VPDB, respectively. The $\delta^{18}O$ and $\delta^{13}C$ values of the majority of the early replacive microdolomites (D1) overlap with the D2 and D4 dolomites (Fig. 12). The heaviest $\delta^{18}O$ values measured in the dolomites (>1‰ VPDB) are heavier than estimates of Oligocene-Miocene carbonates, suggesting the involvement of evaporative brines and/or salinity-elevated seawater in the dolomitization process.

### DISCUSSION

**Stabilization of skeletal and non-skeletal components**

Petrographic and stable isotope evidence suggest that skeletal and non-skeletal (e.g. micrite) components in the Asmari Formation underwent variable degrees of diagenetic stabilization (Fig. 12). Many of the originally low-Mg calcitic components such as...
foraminifera together with aragonitic components (e.g. corals and molluscs) and high-Mg calcitic components (e.g. red algae) were altered, as evidenced by partial to complete recrystallization / dissolution and depletion in their δ¹⁸O values relative to Oligocene-Miocene marine carbonates (Allan and Wiggins, 1993) (Fig. 11). In most of the analyzed carbonates except some of equant calcites, the δ¹³C signature appears to be buffered by the precursor carbonates while retaining their original δ¹³C values.

The original matrix of the studied carbonates has been subjected to variable degree of recrystallization, as indicated by an increase in crystal size and by modification of the original δ¹⁸O values (Fig. 11). The samples are represented by moderately negative to slightly positive values for δ¹⁸O. Their stable isotopic compositions overlap with altered fossils and equant calcite cements.

For the least altered skeletal and non-skeletal components, the δ¹⁸O values, which are depleted compared to postulated values for shallow-marine Oligocene-Miocene marine carbonates, may indicate warmer temperatures and higher sea levels, possibly associated with calcite precipitation. Conversely, the heavy δ¹⁸O values associated with shallowing events appear to be related to lower sea levels and cooler bottom-water temperatures. The oxygen–isotope curve compiled by Zachos et al. (1997) provided a proxy for global climate and sea level (polar ice volume). The late Oligocene and early Miocene periods have generally been viewed as times of moderate climatic warmth and ice-free conditions. A δ¹⁸O value of seawater of around -1.0‰ is assumed for the Miocene (Zachos et al., 1997). However, it is not clear how accurately these open-marine values reflect the δ¹⁸O of Asmari seawater in the restricted Zagros basin. Since evaporation can lead to an enrichment of seawater δ¹⁸O, the Asmari seawater may have had a value of +1‰ or even higher (Craig, 1965).

**Calcite cementation**

Calcite cementation resulting in early lithification of the Asmari Formation and porosity occlusion. Primary porosity was occluded by non-ferroan bladed, prismatic isopachous rim calcite (C1; Fig. 6A) and syntaxial overgrowth rim calcite (C2) which is non-luminescent, indicating syndepositional cementation (c.f. Steinhauff, 1989). This suggests that early cementation with isopachous calcite occurred in a marine phreatic environment.

The non-ferroan calcite cements (C3 and C4) occluding intraparticle pore spaces and fractures have dull luminescence and display cross-cutting relationships with earlier diagenetic features. The δ¹⁸O and δ¹³C values of some of the equant and blocky calcite cements show a distinct positive trend (r² =0.78), which may reflect increasing water-rock interaction (cf. Frank and Lohmann, 1996) and/or exposure to meteoric fluids. This linear correlation may also indicate that the isotopic compositions of both elements were controlled by temperature-dependent fractionation (Ghazban et al., 1990; Ghazban and Al-Aasm, 2007). The δ¹⁸O values of carbonates normally responds to the temperature of formation and the δ¹⁸O of the water. The δ¹⁸O of these calcites confirm the interpretation of their formation.
under relatively warm temperature conditions or in the burial environment. Such a clear relationship between $\delta^{13}$C and $\delta^{18}$O may also be due to variable mixing of fluids with two end-member compositions (Fig. 12): a hot hydrocarbon-bearing fluid which perhaps originated from a deeply-buried source rock; and a cool, oxidized meteoric fluid.

The $\delta^{13}$C values of calcites ranges from -8.81 to 0.14‰VPDB. The markedly negative $\delta^{13}$C calcite values may be due to the influence of meteoric waters, but are more often interpreted to reflect an input of oxidized organic carbon. Additionally, the data may suggest a hybrid carbon source including both seawater and hydrocarbons (Ghazban and Al-Aasm, 2007). Thus $\delta^{13}$C-depleted calcites may be derived from the oxidation of hydrocarbons; while calcite with less negative values was derived from sea water containing relatively $\delta^{13}$C-enriched bicarbonate.

**ORIGIN OF DOLOMITE**

**Early replacive microdolomite (D1)**

Any mechanism which can explain the origin of early replacive microdolomite (D1) must also be able to account for its precipitation very early in the diagenetic history of the Asmari Formation, and its association with burrowed, mottled, fenestral carbonates intercalated with primary nodular anhydrite (Tables 1, 2). Petrographic evidence shows that this dolomite precipitated before appreciable physical and chemical compaction. The dolomite appears to have preserved its isotopic signatures (Fig. 12). In addition, the fine crystalline size, non-ferroan nature and lack of visual CL characteristics indicate that the dolomite replaced carbonate mud and selected allochems, suggesting penecontemporaneous dolomitization. Such dolomite commonly forms in layers from evaporitic brines in sabkha-type environments, similar to Quaternary sabkha dolomitization in the Persian Gulf (e.g. Pursar, 1973; Chafetz et al., 1999). Such layers may develop penecontemporaneously within a carbonate platform or ramp from brine reflux related to the sinking of saline brines from sabkha mudflats. This is consistent with Aqrawi et al., (2006) and Stephenson et al. (2007), whose observations imply that fine-crystalline pervasive dolomites in the Asmari Formation were formed by seepage reflux of evaporative brines concentrated in shallow lagoons or sabkhas, and were commonly associated with evaporite deposition.

Hypersaline fluids usually form finely crystalline and geochemically distinct dolomite as a replacement and/or as cements, with the resulting dolostones being laterally extensive and relatively thin (Machel, 2005). A sabkha environment which is characterised by high evaporation rates could have resulted in the high $\delta^{18}$O values observed in these dolomites, while partial recrystallization is supported (Fig. 12) by increased crystal size and slight negative shifts in $\delta^{18}$O (Fig. 9). Recrystallization of early-formed dolomite may be a common process during progressive burial of dolomite, resulting in a negative shift in $\delta^{18}$O signatures (Al-Aasm and Packard, 2000).
Dolomitization in the Oligocene-Miocene Asmari Formation, Gachsaran area, SW Iran

Fine to medium crystalline matrix dolomite (D2)
Formation of D2 dolomite formation coincides with or slightly post-dates that of D1 dolomite. This dolomite (D2) predominantly occurs in grainstone facies (Table 1; Fig. 5), and consists of planar-, non-ferroan micro- to medium crystalline with cloudy brown inclusion-rich cores and clear inclusion-free rims and shows non to dull CL patterns (Table 2). This suggests that this dolomite may be a recrystallized form of D1, as well as replacing allochems in grainstone facies. Further evidence of recrystallization of this dolomite after microcrystalline dolomite is indicated by SEM identification of intracrystalline dissolution pits in the cores of pervasive dolomite rhombs and thin, relatively pit-free rims (Fig. 8C). Furthermore, the overlap in isotopic composition between these two types of dolomite may also suggest some degree of recrystallization of the latter type (Fig. 12). However, some samples of D2 have slightly negative δ^13C signatures, which may also suggest a contribution from an oxidized carbon source or oxidized hydrocarbons.

Saddle-like and zoned dolomite (D3 and D4)
These two types of dolomite are of minor importance and mostly occlude fractures and vuggy porosity (Table 2). They formed during intermediate burial (Fig. 5) at temperatures within the oil window, and saddle dolomite may form in association with hydrocarbons (Tucker and Wright, 1990). The association of these dolomites with fractures (fractures 3 and 4; Table 2) and compaction features further supports this interpretation. These dolomites also show inclusion-rich cores and inclusion-free rims. Sibley (1982) suggested that cloudy centres develop because initial dolomitizing fluids were saturated with respect to low-Mg calcite, minute crystals of which were therefore included in the early rhomb centre.

The occurrence of zoned and saddle dolomites in carbonate reservoirs has been described by numerous authors (see Spötl and Pitman, 1998, for review). The dolomites occur as cement, filling pores, fractures and voids, and as replacement of pre-existing carbonate components. They are in general interpreted to reflect precipitation from hydrothermal fluids (Al-Aasm, C4
W/R interaction
C3
D4
D3
D2
C4
D3
D2

Fig. 13. Oxygen isotope-water fractionation curves for calcite (broken lines) and dolomite (solid lines) derived from equations of Friedman and O’Neil (1977) for calcite and Land (1983) for dolomite. Outlined fields for calcite cements and dolomite phases show that the formation of calcite cements and dolomite generations at temperatures between 25°C and 80°C (obtained by fluid inclusion measurements and inferred from the paragenetic sequence) has occurred from fluids that were affected by increasing temperature, brine enrichment and increasing water/rock interaction.
Evolution of diagenetic fluids

Petrographic and stable isotope data can be used to infer changes in the composition of diagenetic pore fluids and assess their impact on porosity in the Asmari Formation. The relationships of the oxygen and carbon isotopic compositions of carbonate minerals in conjunction with the paragenetic sequence (Fig. 5) elucidates the evolution of the related evaporative brines. The pathway presented here (Fig. 13) reflects changes in temperature (increasing burial) and fluid chemistry due to evaporation, with later modification due to water-rock interactions during burial.

The consistency in \(\delta^{18}O\) values between syndepositional (D1) and late dolomites (D3 and D4) appears to have been caused by simultaneous increases in the \(\delta^{18}O\) and temperatures of the brines involved. Early syndepositional dolomites formed from brines with a heavy \(\delta^{18}O\) signature due to evaporation of initial seawater in a sabkha-type setting. To maintain the syndepositional \(\delta^{18}O\) signature for the precipitation of later dolomites, the involvement of enriched brines with \(\delta^{18}O\) values different from those of Oligocene-Miocene seawater at elevated temperatures is required.

It is envisaged that the average temperature of precipitation of the late dolomite exceeded the syndepositional temperature. Minimum burial of the Asmari Formation in the study area was over 2 km (Ala, 1982; Ghazban, 2007). Assuming a geothermal gradient of 30°C/km and a surface temperature of about 20°C, 2 km of burial translates into temperatures of ca 80° C. These are in good agreement with temperature values obtained from fluid inclusions in late dolomite (F. Nader, pers. comm., 2009) which range from 45 to 100 °C for the Asmari with salinities of around 20 wt% NaCl. Fluids in the pore spaces in Asmari carbonates may have originated from connate seawaters or residual evaporitic brines formed during the deposition of the Kalhur Member or later during deposition of the Gachsaran evaporites. The \(\delta^{18}O\) of initial brines is recorded in the \(\delta^{18}O\) values of early dolomite. The \(\delta^{18}O\)-enriched brines continued to be present during evaporation to the point of gypsum precipitation, and these brines eventually displaced connate waters and seeped downwards through the permeable carbonates. \(\delta^{18}O\) enrichment by these types of residual brines could have been up to +6 ‰ (cf Knauth and Beeunas, 1986; Rostron and Holmden, 2003).

Modification of the original marine pore waters due to increasing water/rock interaction and temperature (from C3 to C4; Fig. 13) may also explain the negative shift in oxygen isotopes in calcitic components and the buffering of carbon isotopes with the original values. The \(\delta^{18}O\) values of calcites are lighter than those of dolomites, and are interpreted here to be the result of isotopic fractionation between the two phases due to a thermal effect. This may explain the stabilization of some fossils and the precipitation of equant cement in early stages.

CONCLUSIONS

In the Gachsaran area of SW Iran, the Oligocene-Miocene Asmari Formation comprises a range of carbonate lithologies (bioclastic grainstones, ooidal and bioclastic, foraminiferal and intraclastic packstones, and mudstones) interpreted to represent deposition in intertidal to subtidal, lagoonal, shoal and low energy settings. Dolomitization has impacted on all carbonate lithofacies to varying degrees and has affected reservoir porosity. Dolomite types are: microcrystalline dolomite; micro-medium crystalline dolomite; saddle-like dolomite; and coarse crystalline zoned dolomite.

Microcrystalline replacive dolomite (D1) is the earliest formed dolomite and is interpreted to have developed in a sabkha environment. Geochemical data indicate that it was slightly recrystallized during exposure to later fluids.

Pervasive micro-medium crystalline dolomite is the most abundant type of dolomite, affected most facies and contributed to reservoir porosity. It likely formed during shallow burial and can be considered as a recrystallized microcrystalline dolomite and occurs before the initiation of chemical compaction and continued through burial. Its isotopic values overlap with D1 which may suggest a common origin from the same fluids, perhaps altered by the incursion of meteoric fluids.

The precipitation of saddle-like dolomite (D3) and coarse crystalline zoned dolomite (D4) is genetically related to fractures. It partially to completely occludes the fractures and vugs that were developed through the dissolution of the earlier carbonate components and rarely replaces earlier matrix dolomite. These fractures may have developed during late Tertiary tectonism. These dolomites also postdate stylolitization and likely occurred during burial. Fluids responsible for the formation of D3 and D4 dolomite cements are affected by brine enrichment and increasing temperatures due to burial.
Reservoir porosity is mostly dominated by microcrystalline pore spaces in muddy, dolomitized matrix and mouldic porosity in grainstone facies. However, reservoir enhancement was largely impacted by the formation of multiple fracture systems that affected Asmari carbonates, especially the dolomitized strata.

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