ANÁLISE DE FÁCIES E ARQUITETURA DE SEQUÊNCIA ESTRATIGRÁFICA EM UMA BACIA DE ARCO TRASEIRO NO IRÃ CENTRAL: UM ESTUDO DE CASO DO MIOCENO INICIAL DA FORMAÇÃO QOM

FACIES ANALYSIS AND STRATIGRAPHIC SEQUENCE ARCHITECTURE IN A BACK-ARC BASIN IN CENTRAL IRAN: A CASE STUDY FROM THE EARLY MIOCENE OF THE QOM FORMATION

آنالیز رخساره‌ای و چارچوب چین‌نگاری سکانسی سازند قم با سن اوایل میوسن در حوضه پشت کمانی واقع در ایران مرکزی

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RESUMO

Os depósitos marinhos da Formação Qom, que é um importante reservatório de gás no Irã Central com a idade do Oligoceno Inicial ao Mioceno Inicial, são estudados para determinar fácies, paleoambiente sedimentar e seqüências deposicionais. A litologia primária é o calcário, que é acompanhado por um conglomerado, marga arenosa, marga e calcário arenoso. Com base no conteúdo siliciclástico, na análise textural e nos constituintes bióticos, dez fácies foram identificadas. Essas fácies pertencem a cinco locais deposicionais, incluindo delta, enseada de maré, lagoa, cardume e mar aberto. De acordo com a ausência de recifes de barreira contínuos e grandes, variação vertical gradual das fácies do ambiente de transição (delta) para o mar aberto raso, a ausência de grãos oncoides, pisoides e agregados que estão principalmente presentes em ambientes com prateleiras de carbonato com aros, a ausência de calciturbiditos e estruturas de queda e deslizamento, a Formação Qom foi depositada em uma rampa homoclinal (rampa interna, média e externa). Estudos de campo e arquitetura de variação vertical de fácies no âmbito de sistemas deposicionais levaram ao reconhecimento de duas seqüências deposicionais de 3ª ordem no tempo do Mioceno Primitivo (Aquitânico). Fácies sedimentares na Formação Qom que ocorreram principalmente no meio da rampa revelam um padrão de empilhamento principalmente agregado nas seqüências deposicionais. A arquitetura estratigráfica das seqüências do Mioceno Primitivo da Formação Qom, com base em gráficos de correlação, é semelhante às seqüências regionais da placa da Arábia e da bacia de Zagros.

Palavras-chave: *Facies, Paleoambiente sedimentar, Estratigrafia de seqüências, Aquitânico, Formação Qom*

ABSTRACT

Marine deposits of the Qom Formation, which is an important gas reservoir in Central Iran with the age of Early Oligocene to Early Miocene, is studied to determine facies, sedimentary paleoenvironment, and depositional sequences. The primary lithology is limestone, which is accompanied by a conglomerate, sandy marl, marl, and sandy limestone. Based on siliciclastic content, textural analysis, and the biotic constituents, ten facies have been identified. These facies belong to five depositional settings, including delta, a tidal inlet, lagoon, shoal, and open marine. According to the absence of continuous and large barrier reefs, gradual vertical variation in facies from the transitional environment (delta) to shallow open marine, the absence of oncoid, pisoid and aggregate grains that are mostly present in rimmed carbonate shelf environments, the absence of calciturbidites and slump and slide structures, the Qom Formation has been deposited in a homoclinal ramp setting (inner, middle and outer ramp). Field studies and vertical facies variation architecture in the framework of depositional system tracts led to the recognition of two 3rd order depositional sequences in the Early Miocene (Aquitanian) time. Sedimentary

facies in the Qom Formation that mainly occurred in the middle ramp setting reveal a mostly aggradational stacking pattern in depositional sequences. The Early Miocene sequences stratigraphic architecture of the Qom Formation based on correlation charts are similar to the regional sequences of the Arabian plate and Zagros basin.

Keywords: *Facies, Sedimentary paleoenvironment, Sequence stratigraphy, Aquitanian, Qom Formation*

چکیده

نهشته‌های دریایی سازند قم به سن اوایل الیگوسن تا اوایل میوسن که یک مخزن گازی بزرگ در ایران مرکزی را تشکیل می‌دهد به منظور تعیین رخساره‌ها، محیط رسوبی دیرینه و چینه‌نگاری سکانشی مورد مطالعه قرار گرفت است. سنگ‌شناسی اصلی در این رخنمون‌ها شامل سنگ آهک است که با لایه‌هایی از کنگلومرا، مارن، مارن ماسه‌ای و سنگ آهک ماسه‌ای همراه است. در منطقه مورد مطالعه بر اساس میزان مواد تخریبی ورودی به حوضه، آنالیز بافت رسوبی و محتوای فسیلی ده رخساره شناسایی گردید. این رخساره‌ها در پنج جایگاه نهشته‌ای شامل دلتا، تایدال اینلت، لاگون، شول و دریای باز نهشته شده‌اند. شواهدی نظیر عدم حضور ریف‌های سدی بزرگ و فاقد تداوم جانبی، تغییرات تدریجی رخساره‌ها در جهت قائم از محیط انتقالی (دلتا) تا دریای باز، عدم حضور دانه‌های آنکوئیدی، پیژوئیدی و دانه‌های آگرگاتی که خاص شلف‌های کربناته بوده و با به ندرت در رمپ‌ها یافت می‌شوند و در نهایت عدم مشاهده کلسی‌توربیدایت‌ها و ساختارهای ریزشی و لغزشی، تاییدی بر نهشت سازند قم در منطقه مورد مطالعه در یک پلاتفرم رمپ هموکلینال از رمپ داخلی تا رمپ میانی و خارجی است. مطالعات صحرایی به همراه نحوه تغییرات رخساره‌ها در چارچوب سیستم تراکت‌های نهشته منجر به شناسایی دو سکانش رسوبی درجه سوم به سن اکتانین در سازند قم گردید. الگوی برانبارش جمعی در سکانش‌های نهشته سازند قم که رخساره‌های رسوبی در آن به طور عمده در محیط رمپ میانی نهشته شده‌اند، غالب است. سکانش‌های نهشته سازند قم به سن اکتانین در برش‌های مورد بررسی دارای مطابقت بالایی با سکانش‌های رسوبی شناسایی شده در حوضه زاگرس و پلیت عربی با سن مشابه است.

کلیدواژه‌ها: رخساره، محیط رسوبی دیرینه، چینه‌نگاری سکانشی، اکتانین، سازند قم

1. INTRODUCTION:

Tectonic activities cause the on-going volcanism during the Late Eocene in Central Iran. These activities led to a regional unconformity in the base of Oligocene deposits (Stocklin and Setudehnia, 1991). This unconformity is overlain by evaporitic and siliciclastic deposits of the Lower Red Formation formed by Late Eocene and Early Oligocene epirogenic movements in Central Iran. Following these marine deposits of the Qom Formation, which is a crucial gas reservoir in Central Iran, is formed with raising of sea-level and a transgression in the Early Oligocene Sea, which lasts till the Early Miocene (Dozy, 1955). The Qom Formation marl, limestone, and siliciclastic rocks have been overlain and underlain with an unconformity by continental deposits of the Lower Red and Upper Red formations, respectively (Stocklin and Setudehnia, 1991; Reuter *et al.*, 2009). The well-known fractured reservoir of the Asmari Formation is isochronous with the Qom Formation (Motiea, 1993).

No type section has been introduced for the Qom Formation, but a type area has been defined for this formation in the Qom Plain in Central Iran microplate (Aghanabati, 2011). In Central Iran, the Qom Formation is deposited with variation in lithostratigraphy, biozone, and microfacies characteristics. The Qom Formation is Oligocene-Miocene in age, based on larger benthic foraminifera biostratigraphy by Yazdi-Moghaddam (2011).

A stratigraphic sequence correlation

between the Qom Formation succession and its comparison with isochronous formations in adjacent areas can explain the depositional model and transgression of the Tethyan Seaway in Central Iran. Since the Qom Formation is a gas reservoir formed in a back-arc basin, this study can help to understand the characteristics of these deposits in the Middle East.

Biostratigraphy of the Qom Formation in this study has been reported as the Lower Eocene age (Aquitanian) by Maghfoori-Moghaddam and Yasboulaghi (2015). The purpose of this research is to describe the depositional setting of the Qom Formation, sequence stratigraphy, and its correlation with the Oligocene-Miocene Asmari Formation in the Zagros Basin.

2. GEOLOGICAL SETTING AND LOCATION OF THE STUDY AREA:

The final collision of the African-Arabian Plate with the Iranian plate, which began in the Mesozoic, formed the microplate of Central Iran (Coleman-Sadd, 1982). The closure of the Neotethys during the Miocene time was the result of the collision of these plates (Harzhauser and Piller 2007, Reuter *et al.*, 2009). This collision has also formed the Sanandaj–Sirjan Basin (a fore-arc basin), Urumieh–Dokhtar magmatic arc (an intra-arc basin), and the Qom Basin (a back-arc basin) as a result of the Zagros oceanic crust (Neotethys) and southwestern Iranian cratonic plate subduction at the north-eastern margin of the Neotethys on the Iranian Plate (Figure 1a). A

volcanic arc system that developed during the Eocene series has separated these basins (Stocklin and Setudehina, 1991). Thus, during the Late Oligocene-Early Miocene, the Qom Formation was deposited in this back-arc basin in the central and northern part of the central Iran microplate (Berberian, 1983). The age, thickness, and lithology of the Qom Formation vary in different sections. These are caused respectively by (1) marine transgression of the Neoethys in the Iranian Plate started from the southeast and continued northwestward gradually, and (2) various positions of the Qom Formation within the Qom back-arc basin (Schuster and Wielandt 1999). Furthermore, the thickness and lithofacies variations seen within the Qom Formation may have controlled regional faults and subsidence and uplift in the Qom basin (Nogol-e-Sadat, 1985).

In this research, two sections have been investigated in the northwestern margin of the back-arc basin of the Qom Basin in Markazi Province. The study sections include Ashtiyan and Kordijan, which are located in north and northeast of Ashtiyan, about 67 km north of Arak City in central Iran (Figure 1b). The Ashtiyan section at the geographic location of 34°32'45"N and 50°01'18"E and the Kordijan section occurred at 34°38'09"N and 50°07'23"E are examined in detail for sedimentological investigation. In these sections, thick to medium and thin-bedded limestone with a few argillaceous limestone beds and marl formed the main lithologies. Some units consist of conglomerate, sandy marl, and sandy limestone that are minor lithologies. In both sections, the Qom Formation is unconformably underlain by the Oligocene Lower Red Formation and overlain by the Miocene Upper Red Formation (Figure 1c and Figure 2).

3. MATERIALS AND METHODS:

The complete sections of the Qom Formation in Ashtiyan and Kordijan were measured and sampled in the Ashtiyan area in north of Markazi Province. In the Kordijan section, with a thickness of 94 m, thirty-four samples have been collected. The thickness of the Ashtiyan section is 103 m, and 25 samples have been studied. The classification of the carbonate rocks is based on Dunhan (1962). The siliciclastic rocks follow the nomenclature of Folk (1980). The composition percentage of allochems in sedimentary rocks is based on the Bacelle and Bosellini (1965) visual diagrams. Samples are stained by potassium ferricyanide and alizarin red-s to distinguish carbonate minerals (Dickson, 1965). Facies classification and their

environmental interpretation are based on textural features, fabric, and biota content following Read (1985), Burchette and Wright (1992), Wright and Burchette (1996), and Flugel (2010). The construction of sequence stratigraphy is based on the environmental changes across limiting surfaces, the landward or seaward stepping following Catuneanu (2006), Catuneanu *et al.* (2009), and Catuneanu (2017).

4. RESULTS AND DISCUSSION:

4.1. Facies Analysis

Ten different carbonate and siliciclastic facies were identified from the Qom Formation in the studied sections. This facies were divided into five facies belts, representing the main depositional paleoenvironments, including delta, tidal inlet, lagoon, shoal, and open marine. The facies have been differentiated based on the sedimentological and paleontological criteria. The general setting is interpreted to be a carbonate ramp system, subdivided into inner, middle, and outer ramp settings following the terminology of Burchette and Wright (1992). Vertical distribution of textures and the identified facies and their relevant paleoenvironment along with sequence stratigraphic architecture of the Qom Formation in the both studied sections are shown in Figure 3.

4.2. Deltaic facies (transitional)

4.2.1 F1: Conglomerate

Conglomerate facies at the base of the Qom Formation in both sections have been seen as massive beds. Carbonate cement is predominant between grains in nearly all samples. Particles vary in size from small sand-size to pebble (<64 mm) — silt and tiny sand-size form the matrix. The particles are sandstone, shale, and limestone fragments, which form a poorly to moderate-sorted and mostly subrounded to angular polymictic conglomerate up to 2-5 m thick. This facies has seen heterogeneous mass with reddish in color (Figures 4a and 4b).

Interpretation: The poorly sorted matrix-supported conglomerates which form coarsening-upwards cycles are attributed to the accumulation of clasts in deltaic environments (Martini *et al.*, 2017; Arp *et al.*, 2019). The mostly red color of the matrix shows the oxic condition in time of deposition. Sedimentological characteristics include graded bedding (coarsening upward), the red color of texture, sand to pebble size of particles with angular to semi-rounded clasts, and its

vertical and lateral changes to carbonate facies reveal high-energy water with high bedload in a deltaic environment system. The source of sediments is from nearby highs of Lower Red Formation that surrounded the Qom back-arc basin and have transported to the basin by river channels along with a short distance. The rounding and sorting associated with this conglomerate and the lithology of the conglomerate features will confirm the short distance and the nearby source rock.

4.3. Tidal inlet facies (inner ramp)

4.3.1 F2: *Bioclastic hybrid arenite*

This facies includes bioclastic carbonate up to 20 percent — the bio-clasts consist of echinoid, brachiopod, operculina, and bryozoan. The matrix is made of carbonate mud, which dolomitized in some portions. Monocrystalline and less polycrystalline quartz grains, which are silt to medium sand in size, formed the major detrital particles. This facies consists of a poorly to well sorted with angular to semi-rounded grains (Figures 4c and 4d).

Interpretation: The bioclastic hybrid arenite is a typical facies in mixed carbonate-siliciclastic environments that their framework is made of detrital clasts. The 'arenite' term suggested for rocks consisting of more than 50 percent detrital clasts that accompanied by carbonate clasts (Zuffa, 1985). Deposition of such facies took place in an attached onshore carbonate platform setting with remarkable nearby high topography that transported a large volume of siliciclastic material into the basin (Friedman and Sanders, 1978; Flugel, 2010; Sengupta, 2017). According to sedimentological characteristics such as open marine bioclasts and stratigraphic position adjacent to carbonate shoal, the depositional setting could be tidal inlet that connected the continental area to the ocean and also channels that transported siliciclastic material from delta to the open marine. The large volume of siliciclastic material confirms the deposition of this facies in a short distance to the source rock and as channels connecting the open marine to the shoreline (Flugel, 2010). The channels are maintained by tidal flow; the presence of open marine biota with siliciclastic material confirms this statement.

4.4. Lagoonal facies (inner ramp)

4.4.1 F3: *Bioclast miliolid packstone*

Despite the packstone fabric, the biotic

variations are low, and the constituents include different species of Miliolidae such as *Quinqueloculina* sp., *Pyrgo* sp., *Triloculina* sp., and *Miliola* sp. echinoid, red algae, bryozoan, and bivalve forms the minor features by <10%. Silt size quartz grains are present by 2-5%. This facies shows medium sorting and rounding and only seen in the Kordijan section (Figure 5a).

Interpretation: Miliolid is predominant in a restricted lagoonal environment (Geel, 2000). Recently, most of the porcelaneous benthic foraminifera live in shallow tropical and sub-tropical environments (Lee, 1990; BouDagher-Fadel, 2008; Benedetti and Frezza, 2016). Thus, this facies deposited in a nearly restricted lagoonal setting above the fair-weather wave base (FWWB). The restricted condition can be confirmed by a low distribution of normal marine biota, low variation of foraminifera, and the predominance of porcelaneous foraminifera. The predominance of porcelaneous foraminifera has also revealed waters with high salinity (Read, 1985; Flugel, 2010).

4.5. Bioclastic shoal (inner ramp)

4.5.1 F4: *Bioclast, red algae rudstone/grainstone*

Sparry calcite cement, including blocky and poikilotopic cement, formed the texture. The major biotic constituents are red algal species such as *Lithophyllum* sp. and *Lithothamnium* sp. with 20-30% in abundance and larger than 2 mm in size. Other major biota include echinoid with overgrowth cement, rotalia, bryozoan, and large fragments of bivalves. Gastropod, miliolid, brachiopod spin, and unknown fragments of hyaline benthic foraminifera form the minor biota. Silt, and small and medium-size quartz grains with 5-7% in abundance form the siliciclastic features. All the features in a sparry texture show medium to good sorting and low to medium roundness (Figure 5b).

Interpretation: According to the abundance and large size of the red algae, it seems that these biota have been deposited in the nearest place to their habitat. The best condition for red algae growth is an environment with high nutrition, sufficient oxygen, the wave energy to provide these materials, and a depth of water where appropriate light can penetrate (Bassi, 2005; Halfar and Mutti, 2005). Textural characteristics, including the absence of micrite, sparry cement between the constituent along with specific sorting and rounding, reveal an environment with medium to high wave energy. Thus, based on the biota and sedimentological characteristics, this facies is

deposited in a bioclastic shoal setting above FWFB in the inner ramp.

4.6. Open marine facies (middle ramp)

4.6.1 F5: Echinoid, bryozoan, red algal packstone/rudstone

This texture has mainly seen as packstone and occasionally with large size red algae bearing biotic constituents as rudstone. The major biota with 30-40% in abundance are bryozoan (0.5-2 mm in size) and *Lithophyllum* sp. and *Lithothamnium* sp. (both 5 mm to larger than 10 mm in size). Miliolid is present with 3-5% in abundance. The minor biota consists of gastropod, rotalia, brachiopod, and worm tubes. Small to medium sand-size quartz grains are present with 5-10% in abundance. The texture has partly dolomitized or filled by sparry calcite cement (Figure 5c).

Interpretation: high abundance and large size of red algae, partly presence of sparry calcite cement between biota, and the presence of dispersed fragments of benthic foraminifera and rotalia can confirm its proximity to the reef assemblages of the bioclastic carbonate shoal. The predominance of carbonate mud in texture along with oligo-photoc biota such as miliolid, and the predominance of photic dependent biota such as red algal species that is also able to grow and develop in oligo-photoc condition indicating the shallowest open marine facies adjacent to carbonate shoal, with high to medium wave energy (Halfar and Mutti, 2005; Barattolo *et al.*, 2007; Brandano *et al.*, 2009). Thus, this facies based on the presence of photic dependent and independent biota is deposited in waters with normal salinity below FWFB in the middle ramp and adjacent to carbonate shoal.

4.6.2 F6: Bioclast, nummulitids, operculina wackestone

The major biotic constituents consist of operculina and nummulites. Echinoid, red algae, brachiopods, bryozoan, and occasionally rotalia form the minor biota in this facies carbonate micrite dolomitized in some parts of the texture. The frequency of quartz grains are 20-30% and vary in size from fine to medium sand (Figure 5d). Interpretation: The predominance of larger benthic foraminifera with a low diameter-thickness (D/T) ratio shows relatively shallow parts of open marine with oligophotic conditions (Geel 2000; Bassi *et al.* 2007). Also, light penetration decrease in the depositional environment reveals by stretched forms of larger benthic foraminifera with low

diameter-thickness (D/T) ratio (Nebelsick *et al.*, 2005; Bassi *et al.* 2007; Khatibi-Mehr and Adabi 2014). Thus, larger benthic foraminifera as the major biota along with echinoid and bryozoan in carbonate mud texture can demonstrate medium to low energy open marine environment between fair-weather wave base (FWFB) and storm wave base (SWB) in the middle ramp (Flügel 2010; Adabi *et al.*, 2016).

4.6.3 F7: Red algae, bryozoan, brachiopod packstone/rudstone

The main biotic constituents are brachiopod, bryozoan, and some echinoid fragments. Red algal fragments show low frequency. Rotalia and miliolid forms minor biota. Small to medium sand-size quartz grains with 5-10% in abundance are dispersed within the matrix. Dolomitization occurred in some parts of the micritic matrix (Figure 5e).

Interpretation: Bryozoan assemblages are common in calm and low energy waters of shallow open marine. Although they are photic independent heterotroph organisms and found independently of water depth (Pomar, 2001; Drinia *et al.*, 2009), nonetheless, the presence of red algae as the main biota with high frequency reveals shallow parts of open marine. A high abundance of red algal fragments defines waters with sufficient light and relatively high energy in front of carbonate shoal (Pomar, 2001). In this facies, the biotic constituents suggest calm and low to relatively medium energy waters with normal salinity. The medium sand-size of red algal fragments and their medium roundness can be indicative of much more movement with greater distance (Perrin, 1995; Brandano *et al.*, 2009). Thus, based on all textural and biotic pieces of evidence, this facies was deposited in low energy open marine setting in middle ramp above SWB.

4.6.4 F8: Echinoid, bryozoan, brachiopod wackestone/floatstone

This texture reveals as wackestone but in a few samples contain bryozoan and brachiopod, larger than 2 mm and even centimeter in size that are floating in a mud matrix reveal as floatstone. The major biota are echinoid, bryozoan, and brachiopod. Small benthic foraminifera such as miliolid is rarely present. Ostracod and unknown micritized biota (peloid) has also present. The frequency of quartz grains is 1-5%, which varies in size from small to coarse sand (Figure 5f).

Interpretation: Echinoid as the main biota has been deposited in relatively deep waters of

open marine in the middle ramp (Barattolo *et al.*, 2007). All the main biota in these facies including bryozoan and brachiopod are photic independent biota and can deposit in relatively deeper parts of open marine settings. Furthermore, these biota are stenohaline and indicators of waters with normal salinity (Holcová and Zágöršek, 2008; Drinia *et al.*, 2009). The low variety and well-preserved coarse grain biotic features, along with the predominance of carbonate mud suggest a low energy depositional environment. The main biotic constituents such as brachiopod, bryozoan, and echinoid with low biotic abundances suggest lower parts of the middle ramp, adjacent and above SWB with limited water circulation.

4.7. Open marine facies (outer ramp)

4.7.1 F9: Sandy mudstone

This facies mainly consists of carbonate mud deposits. Silt and small sand-size quartz grains are scattered through the matrix with a 10-20% frequency. Glauconite is observed with minor amounts. Unknown shell fragments have also been present. This facies in hand specimen is dark cream to light gray. Pyritization occurred in the matrix (Figure 5g).

Interpretation: During a sea-level rising or subsidence in a sedimentary basin, carbonate deposits are drowned, and deep water limy mud is dominant (Tucker and Wright, 2009). All evidence including the presence of glauconite, pyritization, and dark color of this facies in both microscopically and hand specimen suggest that deposition took place in low energy and anoxic waters of open marine in an outer ramp setting below SWB.

4.7.2 F10: Shaly mudstone

Shaly mudstone facies includes the marl lithology interval of the Qom Formation in the Kordijan section. The rocks showing these facies are microscopically light gray, and in hand specimen is gray. Silt size quartz grains are scattered within the matrix in a minor amount. Shaly mudstone facies are completely homogenous, and no biota or shell fragments have been observed (Figure 5h).

Interpretation: During the sea-level rise, mudstone and shale can be formed in deep waters of open marine settings. The lime and clay that formed the shaly mudstone occur as suspended and will precipitate in a low energy marine environment. Thus, according to their stratigraphic position, which is taking place above open marine

limestone strata, they have deposited in a low energy condition below SWB in an outer ramp setting. This facies belongs to relatively deep waters with no biotic fragments, and due to its distance from land and the source area, there are no siliciclastic materials.

The description and characteristics of the identified sedimentary facies, as well as facies associations and some of their main features recognized within the studied sections, are summarized in Table 1.

4.8. Sedimentary Environment

Due to the specific characteristics of the Qom Basin and its widespread in microplate of Central Iran along with high facies variation, thickness, and back-arc geometry, a distinct sedimentary model for different parts of Iran, is impossible. Based on sedimentological and biological data in surface and subsurface sections, different sedimentary models are suggested for deposition of the Qom Formation by many researchers, e.g. a homoclinal ramp by Reuter *et al.* (2007), Saddighi *et al.* (2012) and Amirshahkarami and Karavan (2015) in Qom Province and Esfahan-Sirjan region. However, a rimmed shelf by Vaziri-Moghaddam and Torabi (2004), and a non-rimmed shelf by Mohamadi *et al.* (2011) have also been proposed.

The factors controlling the rate and type of carbonate production are nutrient, light, temperature, salinity, water depth, and chemistry. These factors, along with geological setting, control the carbonate platform geometry and determine the grain type, grain distribution, and the rate of carbonate factory (Brandano *et al.*, 2009).

Facies analysis based on lithology, sedimentary structures, texture, and biotic and abiotic features from the studied sections of the Qom Formation led to the recognition of ten facies deposited in five subenvironments, including delta, a tidal inlet, lagoon, shoal, and open marine. Palaeoenvironmental reconstruction based on the identified facies suggests a homoclinal carbonate ramp for the Qom Formation in the studied area (Figure 6). This suggestion is supported by some evidence including the absence of continuous and large barrier reefs, gradual variation in facies from delta to shallow open marine, the absence of calciturbidites, and slump and slide structures, and lack of oncoid, pisoid and aggregate grains that are mostly present in rimmed carbonate shelf environments. Burchette and Wright (1992) divided a carbonate ramp into an inner ramp

(above FWWB), middle ramp (between FWWB and SWB), and outer ramp (below SWB). Sedimentary facies in the Qom Formation mainly occurs in the middle ramp setting.

The inner ramp includes delta, tidal flat, lagoon, and shoal facies respectively recognized by occurrence of coarsening upward massive polymictic conglomerate (F1, delta), bioclastic hybrid arenite including high sand and open marine biota (F2, tidal flat), porcelaneous foraminifera in a carbonate mud matrix (F3, lagoon), and abundance of red algae accompanied by open marine biota and siliciclastic sediments in a sparry texture (F4, shoal).

The middle ramp consists of four facies from proximal (adjacent to shoal) to distal (adjacent to SWB) part. The middle ramp in the proximal part is characterized by larger benthic foraminifera (e.g. operculum and nummulitids), and shoal derived bioclasts such as red algae in a packstone and rudstone texture (F5-6). The distal parts of the middle ramp include mainly photic independent heterotroph and stenohaline organisms (such as bryozoan and echinoids) that are indicators of normal salinity waters of open marine (Drinia *et al.*, 2009).

The outer ramp is characterized by sandy and shaly mudstone with pyritization in the matrix that is evidence of relatively deep waters with anoxic condition and small unknown shell fragments and glauconite (F9-10).

4.9. Sequence Stratigraphy

A stratigraphic sequence model defines depositional sequences as genetically related chronostratigraphic units that are representative of a single cycle of relative sea-level rise and fall, bounded by unconformity surfaces (e.g. Posamentier and Vail, 1988; Van Wagoner *et al.*, 1990; Posamentier and James 1993; Catuneanu *et al.*, 2006). Retrogradational, aggradational, and progradational stacking patterns in the framework of a depositional sequence are developed due to eustatic sea-level fluctuations.

The stratigraphic sequence interpretation that is proposed for the Qom Formation is based on age, field description, and the broad paleoenvironmental inferences revealed by facies analysis and stacking patterns of facies (Figure 3). In the carbonate platform of the Qom Formation with predominant of warm climate, which is Early Miocene (Aquitania) in age, the sequence boundaries are characterized by siliciclastic facies

(delta and tidal inlet). The depositional sequences consist of three systems tracts, including lowstand system tract (LST), transgressive system tract (TST), and highstand system tract (HST). Each sequence comprises complex facies of subtidal, including lagoon, shoal, and open marine, which covered by siliciclastic facies. The maximum flooding surface (F9-10) is characterized by water deepening and the maximum transgressive in seawater, which is defined by outer ramp facies association. Vertical facies variations and identified environments connected with relative sea-level changes led to the identification of two third-order depositional sequences in the Qom Formation (Figure 3).

4.9.1 Depositional sequence 1 (DS1)

The depositional sequence 1 with the age of Aquitania is 70.75m and 58.07m thick, respectively, in Kordijan and Ashtian sections. The DS1 is divided into LST, TST, and HST. The delta massive conglomerate beds of F1, which is a transitional environment, formed the basal part of DS1. The enormous conglomerate in both sections is deposited over the sandstone beds of the Oligocene Lower Red Formation (Figure 3). The basal deltaic conglomerate with a coarsening upward sequence has been deposited during the period of falling sea level as an LST. The overlying carbonate rocks with shoal and middle ramp facies association of F4 (shoal), F5, F7, and F8 (all open marine: middle ramp) have been deposited during the period of sea-level rise and are interpreted as transgressive system tract (TST) with retrogradational stacking pattern. The TST is characterized by packstone, grainstone, rudstone, and floatstone textures with normal waters biota such as rotalia, red algae, bryozoan, and Echinoidea. The photic independent of open marine biota reveals a rise in sea level that reaches the maximum, equivalent to the maximum flooding surface (MFS). The sandy and shaly mudstone of the F9 and F10 with glauconite and shell fragments and pyritization in matrix characterize the MFS. The main packstone and rudstone textures of the lagoon (F3), shoal (F4), and open marine (proximal middle ramp facies association: F5-6) with mainly aggradational and a few progradational stacking pattern that overlies the MFS characterize the HST. The upper part of the HST is characterized by bioclast hybrid arenite (F2) in both sections and indicate the tidal inlet environment and a type 2 sequence boundary (SB2).

4.9.2 Depositional sequence 2 (DS2)

The depositional sequence 2 is 23.75m thick in the Kordijan section and 43.92m thick in the Ashtian section with the age of Aquitanian. The DS2 can be subdivided into TST and HST (Figure 3). The carbonate rocks of middle ramp facies association (F5-7) with retrogradational stacking patterns are formed during a period of sea-level rise and are interpreted as transgressive deposits of TST (Figure 3). The facies of TST (F5-7) consist of larger benthic foraminifera such as Nummulitidae and Operculina as well as red algae, brachiopod and bryozoan. Large fragments of bryozoan and brachiopod along with Nummulitidae and broad and flat operculina, larger than 2mm in size with rudstone texture, are terminated in outer ramp facies association (F9-10) with evidence of low energy and anoxic condition of relatively deep waters. These facies indicate a maximum increase in sea-level changes, equivalent to the MFS. The mostly packstone and rudstone textures of shoal and proximal middle ramp facies association with dominant of benthic foraminifera (e.g. rotalia) and red algae are overlain by the MFS. These sediments are interpreted as deposition of the HST with a progradational stacking pattern (Figure 3). The upper part of the HST is characterized by bioclast hybrid arenite (F2: tidal inlet) in the Ashtian section and bioclast, red algae rudstone/grainstone (F4: shoal) in the Kordijan section indicating tidal inlet and shoal environments. The Upper Red Formation of Miocene age overlies the DS2 in both sections. There is a type 1 sequence boundary (SB1) between the Qom Formation and the Upper Red Formation.

4.10. Correlation of Depositional Sequences

Precipitation of carbonate sediments is influenced by subsidence and sedimentation rate that are related to the tectonic evolution of the belts that surrounded the Qom back-arc basin. The Oligocene-Miocene sedimentary rocks of the Qom Formation in microplate of Central Iran have some similarities with the Oligocene-Miocene sedimentary deposits of the Asmari Formation in the Zagros Basin and the equivalent formations in the Arabian Plate. For instance, the biotic constituents are the same, and the sedimentary paleoenvironments are a homoclinal ramp system; however, according to the geological setting these basins have not been connected during the Early Miocene. Sharland *et al.* (2001, 2004) and Simmons *et al.* (2007) in Arabian Plate have defined a set of regional maximum flooding surfaces (MFS). They have used MFS for

subdividing the sedimentary succession of the Arabian Plate into a series of synchronous packages. These packages, which are genetic stratigraphic sequences (Galloway, 1989) took place within a set of Tectonostratigraphic Megasequences (TMS) that subdivide the geological history of the Arabian Plate from Precambrian to the Present. These TMS are defined as the package of sediments lying between the unconformity marking both the onset of Red Sea Rifting and the first continental collision between Arabia and Eurasia and the present-day topographic surface. The Qom Formation with the age of Oligocene–Miocene sits within the latest of the TMS (AP11), which is defined as sedimentary packages that took place between two signs of unconformity (Sharland *et al.*, 2001, 2004). The correlative sequence boundaries between Sharland *et al.* (2001, 2004), Simmons *et al.* (2007) and this study with increasing age are as following (Figure 7):

1. The Ng20 SB is equal to the type 1 SB at the top of DS2.
2. The Ng10 SB is equal to type 1 SB at the base of DS1.

The previous sequence stratigraphic studies on Oligo-Miocene deposits of the Zagros Basin include Ehrenberg *et al.* (2007) and Van Buchem *et al.* (2010). In their studies of the Oligo-Miocene Asmari Formation in Dezful Embayment and Izeh zone located in the southwest of Iran defined seven sequence surfaces that were dated and correlated between several outcrops and sub-surfaces wells. Among these sequence surfaces with the Early Miocene (Aquitanian) age of the Qom Formation three sequence boundaries are correlative with those of Ehrenberg *et al.* (2007) and Van Buchem *et al.* (2010). With increasing age, these surfaces are as following:

1. Bu20 SB and SB VI is equal to the type 1 SB at the top of DS2.
2. Aq20/Bu10 and SB V is equal to the type 2 SB between DS1 and DS2.
3. Aq10 and SB IV is equal to the type 1 SB at the base of DS1.

In this study, three recognized sequence boundaries are well-matched with the sequence boundaries that are proposed by Ehrenberg *et al.* (2007) and Van Buchem *et al.* (2010) (Figure 7).

5. CONCLUSIONS:

Based on field observations, textural analysis, and biotic constituents, ten facies have

been identified. The Early Miocene (Aquitania) Qom Formation in the Qom back-arc basin in the microplate of Central Iran has been deposited in a homoclinal ramp setting including delta, a tidal inlet, lagoon, shoal, and open marine subenvironments. The absence of continuous large barrier reefs, pisolite, oncolite, slump structures, and calciturbidites support this suggestion. The Qom Formation in studied sections mainly occurs in an open marine setting. Furthermore, based on sequence stratigraphic studies, two third-order depositional sequences in the Aquitania of the Qom Formation have been recognized. Based on the chronostratigraphic sequence correlation, these depositional sequences have a good correlative architecture with Arabian Plate sedimentary successions and the sequences that have been recognized for the Oligocene-Miocene Asmari Formation in Dezful Embayment and Izeh zone in the southwest of Iran by other researchers.

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Figure 1. Geological setting, location, and geological map of the study area; (a) a general map showing the distribution of the Qom Formation in different basins of Iran including QB or Qom Basin (Back-arc basin), UDMA or Urumieh–Dokhtar Magmatic arc (Intra-arc basin), and SSB or Sanandaj–Sirjan Basin (Fore-arc basin) (adapted from Reuter et al., 2009); (b) Location of the studied area in the Qom back-arc basin; (c) Geological map of the study area, showing the Oligocene–Miocene of the Qom Formation and underlying and overlying formations (adopted from geological survey of Iran).

Figure 2. A general view of sections. (a), (b) and (c) showing the Qom Formation with underlying Upper Red Formation and overlying Lower Red Formation in Ashtian section; (d) and (e) basal conglomerate of the Qom Formation that overlain Lower Red Formation in Kordijan section; (f) view of the Qom Formation boundary with Upper Red Formation in Kordijan section.

Figure 3. Vertical facies distribution showing paleoenvironmental and sequence stratigraphic characteristics of the Qom Formation in studied sections in the Qom Back-arc Basin.

Figure 3. Continue

Figure 4. Facies types of the Qom Formation in Ashtian and Kordijan sections. (a) and (b) F1: Conglomerate facies showing coarsening upward sequences (transitional, delta); (c) and (d) F2: Bioclastic hybrid arenite with open marine bioclast features of open marine such as red algae, echinoid, and bryozoan (inner ramp, tidal inlet).

Figure 5. Different facies types of the Qom Formation in Ashtian and Kordijan sections. (a) F3: Bioclast miliolid packstone (inner ramp, lagoon); (b) F4: Bioclast, red algae rudstone/grainstone (inner ramp, shoal); (c) F5: Echinoid, bryozoan, red algal packstone/rudstone (middle ramp, open marine below FWB); (d) F6: Bioclast, nummulitids, operculina wackestone (middle ramp, open marine below FWB); (e) F7: Red algae, bryozoan, brachiopod packstone/rudstone (middle ramp, open marine below FWB); (f) F8: Echinoid, bryozoan, brachiopod wackestone/floatstone (middle ramp, open marine below FWB); (g) F9: Sandy mudstone (outer ramp, open marine below SWB); (h) shaly mudstone (outer ramp, open marine below SWB).

Figure 6. Homoclinal carbonate ramp depositional model proposed for the Qom Formation. FWWB (fair-weather wave base), SWB (storm wave base)

Age	Epoch	Stage	Arabian Plate Sharland et al., 2001/2004; Simmons et al., 2007	Dezful Embayment and Izeh zone (SW Iran)	
				Ehrenberg et al., 2007	Van Bachem et al., 2010
20	Lower Miocene	Burdigalian	17.5 Ng20		
			19.0 Ng20 SB	18.5 Base Gachsaran	18.5 SB VII
		Aquitainian	20.0 Ng10	20.2 Bu20 SB	20.2 SB VI
				21.6 Aq20/Bu10 SB	21.4 SB V
			23.0 Ng10 SB	23.0 Intra-Aq10 Aq10 SB	23.2 SB IV
	Oligocene	Chattian	24.5 Pg50	24.9 Ch30 SB	25.1 SB III
				28.0 Ch20 SB	
		Rupelian	29.0 Pg40	28.9 Ru30/Ch10 SB	28.8 SB II
				30.0 Ru20 SB	
			30.0 Pg30 33.5 Pg30 SB		34.0 SB I

Figure 7. Comparison of sequences of the Qom Formation with the Oligocene-Miocene Asmari Formation in Dezful Embayment and Izeh zone in southwest of Iran and Arabian Plate sedimentary successions

Table 1. Facies type, facies associations and depositional environments of the Qom Formation in the studied sections.

Facies code	Facies type	Lithology	Facies characteristics	Grain size	Sorting	Energy level	Flügel (2010) (SMF/RMF)	Depositional environment	Facies association
F1	Conglomerate	Polimictic-conglomerate	Massive heterogenous Conglomerate with Silt and very small sand as the matrix that is formed of sandstone, shale and limestone.	Pebble/sand	Poorly	High	-	Delta	Transitional
F2	Bioclastic hybrid arenite	Limy sandstone	Includes carbonate bio-clasts consists of echinoid, brachiopod, operculina, and bryozoan up to 20 percent. The matrix is made of carbonate mud. Monocrystalline and less polycrystalline quartz grains formed the major detrital clasts.	Sand	Poorly to medium	High	-	Tidal inlet	
F3	Bioclast miliolid packstone	Limestone	Biotic features variation are low and includes different species of Miliolidae. Echinoid, red algae, bryozoan, and bivalve forms the minor features by <10%.	Sand/mud	Poorly to medium	Low	SMF18/RMF20	Lagoon	Inner ramp
F4	Bioclast, red algae rudstone/grain stone	Limestone/sandy limestone	The major biotic constituents are red algae, echinoid, Rotalia, bryozoan, and bivalves in a spary texture. Gastropod, miliolid, brachiopod, and fragments of larger benthic foraminifera form the minor biota.	Pebble/sand	Medium to good	High	SMF13/RMF27	Shoal	
F5	Echinoid, bryozoan, red algal packstone/rudstone	Limestone	The major biota are bryozoan and <i>Lithophyllum</i> sp. and <i>Lithothamnium</i> sp. Miliolid is present by 3-5% abundance. The minor biota are include gastropod, Rotalia, brachiopod, and worm tubes.	Pebble/sand	Poorly	Medium to high	SMF18/RMF14	Open marine (below FWWB)	
F6	Bioclast, nummulitids, operculina wackestone/floatstone	Limestone	The main biotic features are include Operculina and Nummulites. Echinoid, red algae, brachiopods, bryozoan, and Rotalia form the minor biota.	Pebble/sand	Poorly	Low to medium	SMF8/RMF13	Open marine (below FWWB)	Middle ramp
F7	Red algae, bryozoan, brachiopod packstone/rudstone	Limestone/sandy limestone	The main biota are brachiopod, bryozoan, and less echinoid fragments. Red algae, Rotalia, and miliolid form the minor biota.	Pebble/sand	Poorly	Low to medium	SMF12 S/RMF8	Open marine (below FWWB)	
F8	Echinoid, bryozoan, brachiopod wackestone/floatstone	Limestone/sandy limestone/argillaceous limestone	The major biota are echinoid, bryozoan, and brachiopod. Miliolid, ostracod and unknown micritized biota have also seen.	Pebble/sand	Poorly	Low	SMF12 C/RMF7	Open marine (below FWWB)	
F9	Sandy mudstone	Sandy marl	Mainly formed of carbonate mud with Silt and small sand-size quartz grains and shell fragments. Glauconite is observed and pyritization occurred in the matrix.	Sand/mud	-	Low	SMF3/RMF2	Open marine (below SWB)	Outer ramp
F10	shaly mudstone	Marl	It is completely homogenous and no biota or shell fragments have been observed. Silt size quartz grains are scattered within the matrix.	Mud	-	Low	-	Open marine (below SWB)	

SMF: standard microfacies type; RMF: ramp microfacies type