by Seyed Mohsen Aleali*

Facies analysis and depositional sequences of the middle Cretaceous Sarvak Formation in the northwest of Behbahan, Zagros basin, Iran

Department of Geology, Science and Research Branch, Islamic Azad University (IAU), Tehran, Iran; *Corresponding author, E-mail: aleali.mohsen@gmail.com

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Sarvak Formation, a thick carbonate succession with the age of Middle Cretaceous, is one of the most significant hydrocarbon reservoirs in the Zagros basin. The Tang-e Solak section of the Sarvak Formation in the Bangestan anticline with a total thickness of about 850 m has been studied, in order to determinate its microfacies types, depositional setting model and depositional sequences. Detailed textural and petrographic analysis led to the identification of 11 microfacies that arranged in three facies associations: inner ramp, mid-ramp, outer ramp and basin. Examination of vertical and lateral facies changes indicated these sediments were deposited in a carbonate ramp depositional system. Frequency analysis of facies indicated outer ramp and basin facies associations are the most frequent facies. Sea level fluctuations during in deposition of Sarvak successions led to formation of two depositional sequences. These depositional sequences are composed of transgressive systems tract and highstand systems tract. The highstand systems tract can be separated into Early HST and Late HST. Stacking pattern in Early HST part is aggradational and in Late HST is progradational.

Introduction

The middle to late Cretaceous carbonates in the petroliferous Zagros basin in Iran are known as the Bangestan Group (James and Wynd, 1965). It includes the Kazhdumi, Sarvak, Surgah and Ilam Formations (James and Wynd, 1965; Motiei, 1993; Aghanabati, 2004) and host giant hydrocarbon reservoirs in southwestern Iran (Fig. 2). Well-known reservoirs of this stratigraphic unit contain the Mauddud, Khatiyah, Ahmadi and Mishrif Formations in the Arabian Peninsula, and the Sarvak Formation in Iran (Alsharhan and Nairn, 1997; Sharland et al., 2001; Sharland et al., 2004; Bordenave and Hegre, 2005; Ghazban, 2007). The Sarvak Formation, a thick carbonate succession of the middle Cretaceous, host one of the richest hydrocarbon provinces of the world that cover most of the Arabian Platform (e.g., Sharland et al., 2001) and formed the second most important reservoir rock in

Zagros basin.

Albian to Turonian age Sarvak Formation (James and Wynd, 1965; Motiei, 1993) in southwest Iran composed of carbonate sequence including limestone and dolostone with subordinate intervals of shale that demonstrated both neritic and pelagic facies (Fig. 2). Detailed facies analysis in different part of Zagros basin has revealed that thickness and facies distribution of Sarvak Formation varies greatly in from place to place. As, this formation composed of shallow marine successions in the south and central parts of Zagros basin and Persian Gulf area and deep marine units in the north and north west of Zagros basin (Lurestan Province). In the Dezful embayment and Khuzestan areas the Sarvak Formation usually exhibits either facies or both (Fig. 1a). Previous studies show that the lateral and vertical facies changes in Sarvak succession are result of relative sea-level fluctuation in middle Cretaceous age that is effected by wide climate and tectonic changes (e.g., Mehrabi and Rahimpour-Bonab, 2014).

The sediments of middle Cretaceous carbonate systems were deposited in carbonate platform under humid tropical to subtropical climates (e.g., Murris, 1980; Scott, 2007; Hollis, 2011, Rahimpour-Bonab et al., 2012a, 2013; Mehrabi et al., 2015). Diagenetic features, depositional environment, sequence stratigraphy and reservoir quality of the Sarvak succession and equivalent in Arabian Peninsula previously studied by many authors (e.g., Alsharhan, 1995; Taghavi et al., 2006; Bashari , 2007a, b; Ghabeishavi et al., 2009, 2010; Piryaee et al., 2010, 2011; Hajikazemi et al., 2010, 2012; Razin et al., 2010; Sharp et al., 2010; Van Buchem et al., 2006, 2011; Cross et al., 2010; Hollis, 2011; Rahimpour-Bonab et al., 2012a, b, 2013; Asadi Mehmandousti et al., 2013; Mehrabi and Rahimpour-Bonab, 2014; Mahdi et al., 2013; Mahdi and Aqrabi, 2014; Mehrabi et al., 2015; Vincent et al., 2015; Esrafilidizaji et al., 2015).

The study area, Tang-e Solak outcrop, is located in southern flank of the Bangestan anticline about 45 km northwest of Behbahan city in Khuzestan Province (Figs. 1b and 3a). In this area, The Sarvak Formation overlies the deep marine shale of the Kazhdumi Formation and is disconformably underlain Gurpi Formation (Figs. 2 and 4a, b). According to Bordenave and Hegre (2010) the principal source of hydrocarbon for the Sarvak reservoir is the underlying Kazhdumi Formation (Figs. 2 and 4a). The main aim of this article is to discuss the facies distribution and depositional setting characteristics, delineate depositional sequences

Figure 1. Location and SRTM map of the studied area in the Izeh zone. (a) Schematic structural map of the Zagros Mountains. From top right to bottom left: Central Iranian block and micro-continents, Urumieh-Dokhtar Arc, Sanandaj Sirjan Zone, Imbricate Zone, Simply Folded Belt, Foreland basin (modified after Falcon, 1974; Homke et al., 2009; Casini et al., 2011). (b) SRTM image of the Bangestan anticline in the study area (white star: Tang-e solak area; a–b line: location of measured section).

and reconstruct the sea-level history during the middle Cretaceous time in the study area.

Geological Setting

Iran is divided into three important geological areas based on two great mountain belts (Zagros Mountains in the south and the Alborz

Mountains in the north of Iran) including Zagros basin, central Iran and Alborz basin (Aghanabati, 2004). The Zagros basin is characterized by 7–14 km of sediment sequences along the north–northeast edge of the Arabian plate, which are deposited over an exceptional long and wide region (Fig. 1a). This petroliferous basin, with a length of more than 1500 km and width between 100 and 300 km, is one of the most significant tectono-stratigraphic units of Iran (Motiei, 1993; Alavi, 2004, 2007).

The Zagros basin was part of the margin of huge Gondwana supercontinent During Paleozoic. It was a Passive margin during Mesozoic periods and a convergent orogen in Cenozoic times.

The Zagros Mountains are the result of Subduction of a passive continental margin on the Arabian Plate under an active continental margin on the Eurasian Plate in the Mesozoic times and Alpine-type orogenic continental collision between Arabia and Eurasia in the Cenozoic times (Stocklin, 1968; Falcon, 1974; Berberian and King, 1981; Jackson and McKenzie, 1984; Beydoun et al., 1992; Talebian and Jackson, 2002). The plate's convergence movement at the eastern edge of the Arabian plate has not been stopped at the present day. This movement is continued at a rate of nearly 25–30 mm/year and in an approximately N-S direction (Berberian, 1995; Tavani et al., 2011).

During the Late Permian through Late Mesozoic, the Zagros Mountain belt was a part of the Arabian southwest Iranian Plate of the northeast Gondwana margin, at equatorial location, at the Neotethys passive margin (e.g., Berberian and King, 1981; Stampfli and Pilleveit, 1993; Scotese and Langford, 1995; Golonka, 2004). Continuously subsided along the main faults in the Mesozoic times was formed several thousands of meters of mainly carbonate rocks in the basin (James and Wynd, 1965; Motiei, 1993; Kashfi, 1992; Alavi, 2004).

Based on stratigraphic framework, structural elements and petroleum habitat, the Zagros basin divided into several main zones including High Zagros, Lurestan, Izeh zone, Dezful embayment, Fars province and Bandar-Abbas Hinterland (Stocklin, 1968; Berberian and King, 1981; Motiei, 1993) (Fig. 1a). The study area (Bangestan anticline) is located 45 km northwest of Behbahan, in the south of the Izeh zone (boundary of the Izeh zone and Dezful Embayment), adjacent to the Izeh-Hendiyan Fault (e.g., Ahmadhadi et al., 2008; Tavani et al., 2011) (Figs. 1b and 3a). The Izeh zone, part of Simply Folded Zagros (SFZ), lies across a sharp topographical break to the southwest of the High Zagros fault (Fig. 1a). This zone comprises of a variety of structures of variable size and geometrical character (Sherkati and Letouzey, 2004). The Bangestan anticline is one of the significant structures in Izeh zone with about 80 km length and 10 km width (Fig. 1b).

Materials and Methods

This research is based on the field and laboratory investigation of the Sarvak Formation from the Bangestan anticline (Tang-e Solak area) of southwest Iran (Figs. 1b and 3a). One section was measured, described and more than 600 thin sections collected and studied to determine petrographic characteristics, facies analysis, depositional setting and depositional sequences. The measured section is continuous (there are no gap) and the thickness of the Sarvak Formation in study area is about 950 meters. Method of sampling was combination of simple random and systematic sampling. All of thin sections were half-stained with Alizarin Red-S to distinguish calcite and dolomite. Carbonate facies are classified based on Dunham (1962) and Embry and Klovan (1971) textural classification schemes. Facies were recognized for each sub-environment according to microfacies characters including carbonate matrix and grain contents, depositional fabric, grain size and type, textural features and energy index (Tucker, 2001; Flugel, 2010). Based on facies characteristics, comparison with ancient and recent environments and standard facies from well-known depositional environments (e.g., Wilson, 1975; Buxton and Pedley, 1989; Burchette and Wright, 1992; Pomar, 2001, Flugel, 2010) the depositional setting of each facies was recognized and interpreted. For determine depositional sequences, sedimentary stacking patterns, sequence boundaries, sequence stratigraphic interpretation and basic sequence stratigraphy concepts were used.

Lithostratigraphy

The Sarvak Formation is part of lithostratigraphic unit of the Middle to Upper Cretaceous Bangestan Group (James and Wynd, 1965) (Fig. 2). In the Tang-e Solak area, Bangestan anticline, the thickness of the Sarvak Formation is about 850 m (Fig. 3a). It is comprised of thin to medium bedded shaley limestone in the lower part, thick bedded to massive limestone in the middle part and medium to thick bedded limestone in the upper part (Figs. 3a–e). Sarvak succession in this

Figure 2. Generalized lithostratigraphic and correlation chart of the Cretaceous successions in the Zagros Fold-Thrust Belt, including Sarvak Formation deposits in the studied area and adjacent regions, adapted from James and Wynd (1965).

Figure 3. Field aspects of the Sarvak Formation in the study area. (a) General view of the Sarvak Formation, in southern flank of the Bangestan anticline northwest of Behbahan city, Izeh zone. (b) Field view of the thin to medium bedded shaley limestone (unit A). (c) Field view of the cream to brown medium to thick bedded limestone (unit C). (d) Field view of the massive middle part limestone, Note that the lower strata are mainly medium to thick bedded, whereas the upper are thick to massive bedded. (e) Field photograph of reddish chert nodules in the middle massive limestone (unit B).

area consists of both shallow water (neritic) and deep water (pelagic) sediments (Fig. 3a). The section was lithologically measured and described bed-by-bed according to layers color, thickness, grain size, fossil content, biogenic and sedimentary structures. Base on the field observations, large-scale lithostratigraphic units in the Sarvak Formation separated into three units (from base to top).

Unit A

The succession of Unit A is composed of 230 m gray to dark gray, thin to medium bedded, fine-grained shaley argillaceous limestone. Planktonic foraminifera and Calcispheres (oligosteginids) are common in this part and this unit signifies a deep marine deposition (Fig. 3b).

This lithostratigraphic unit conformably overlies the deep marine dark gray argillaceous limestone of the Kazhdumi Formation with a sharp contact (Fig. 4a).

Unit B

This unit is composed of 510 m cream to light brown, thick bedded to massive limestone with reddish chert nodules (Figs. 3d and e). Large rudist debris, foraminifers, calcareous algae, mollusks and echinoderms are major fossil contents. This succession illustrates a full transition from deep to shallow water marine environments (from unit A to B).

Unit C

This unit with a thickness of 110 m is consist of dark cream to brown, medium to thick bedded limestone with chert nodules (Fig. 3c). The top of this unit is characterized by 36 m red-weathered beds (Fe oxides staining) that show sedimentological evidence of subaerial exposure (Fig. 4b). As this reason, the Upper boundary in this unit with the marls and shales of the Gurpi Formation is sharp and indicated erosional

disconformity (Fig. 4b). This disconformity is equivalent to Late Cenomanian–Early Turonian (C–T) disconformity (92 Ma) that is documented in south and southwest of Iran and in some parts of the Arabian plate (e.g., Immenhauser et al., 2000; Van Buchem et al., 2002, 2011; Sharp et al., 2010; Vincent et al., 2010; Hollis, 2011; Hajikazemi et al., 2012; Rahimpour-Bonab et al., 2012a, 2013).

Facies Descriptions and Interpretations

The Sarvak succession in the Tang-e Solak area (Bangestan anticline) contains of shallow to deep-water carbonate facies. The major facies constituents are significant variety of skeletal grains, non-skeletal grains, calcite cements and micrite. Rudist debris, benthic and planktonic foraminifera, oligostegina, crinoids/echinoids, bivalve, gastropods, ostracods and sponge spicules are the most skeletal components. The dominant non-skeletal grains are peloids and intraclasts. On the basis of petrographic examination, sedimentary characteristics, facies constituents, textures and fossil contents 11 microfacies are distinguished for the Sarvak Formation in the studied area, which can be organized to three main facies associations including inner ramp, mid ramp, outer ramp and basin (Figs. 5–9).

Inner Ramp Facies Association

MF1: Benthic foraminifera wackestone

This microfacies is characterized by the presence of diverse benthic foraminifera in fine grained mud-supported texture. Large benthic foraminifera (porcelaneous wall benthic foraminifers) such as miliolid, orbitolinid, alveolinid, Nezzazata, Dictyoconus, Pseudolituonella are the principal components. They comprise 40% to 60% of the grains. Green algae debris, calcareous sponge spicules, gastropods are also present as subordinate grains of this facies. This microfacies is a sparse biomicrite according to Folk (1962) (Fig. 5a).

MF2: Benthic foraminifera bioclast wackestone to packstone

In this microfacies, texture varies from bioturbated wackestone to packstone. The main biota are porcelaneous wall benthic foraminifera such as miliolid, orbitolinid, alveolinid, nezzazata, chrysalidina, dicyclina, bivalve shells, green algae, rudist debris, gastropods and echinoderms. Peloid and intraclast (rare) grains also are existence as non-skeletal constituents. The matrix is homogenous micrite (Fig. 5b).

MF3: Bioclast rudist debris packstone

The bioclast content is formed by coarse rudist debris, bivalves, echinoid/crinoid, gastropods, green algae and large to small benthic foraminifera. The size of bioclasts in this microfacies is very various (ranging in size from 200 μ m to 2 mm). Rudist debris comprises 20 to 45% of the grains and exhibit variation in size. Bivalve and rudist debris are mostly coated by a micrite envelope, with the interior filled with spatic microcrystalline calcite. Peloid also is a less common constituent. Skeletal debris are surrounded by micritic fine grained matrix (Fig. 5c). This microfacies is a packed biomicrite according to Folk (1962).

Environment interpretation

The thickest interval of the inner ramp (mainly lagoon) deposits is

Figure 4. Field aspects of the Sarvak Formation in the study area. (a) Outcrop photograph showing lower (basal) boundary of the Sarvak Formation with the underlying soft-weathering Kazhdumi Formation. (b) Outcrop photograph showing sharp contact between Sarvak Limestone and overlying soft-weathering Gurpi Formation. Note that red-weathered beds (Fe oxides staining) and erosional disconformity in the uppermost beds of Sarvak Formation.

Figure 5. Photomicrographs of the main carbonate microfacies types of the Sarvak Formation. (a) MF1: Benthic foraminifera wackestone. (b) MF2: Benthic foraminifera bioclast wackestone to packstone. (c) MF3: Bioclast rudist debris packstone. (d) MF4: Rudist framestone/boundstone. (e) MF5: Rudist debris grainstone. (f) MF6: Rudist debris bioclast grainstone.

existent in the upper part of the Sarvak Formation (upper Sarvak) and is approximately 130 m thick. High-diversity of imperforate porcelaneous wall benthic foraminifers and presence of mud-rich texture with oligotypic fauna (such as miliolids) exhibit a low to moderate energy shallow subtidal environment in this facies association (e.g., Purser and Evans, 1973; Tucker and Wright, 1990; Alsharhan and Kendall, 2003; Bachmann and Hirsch, 2006; Flugel, 2010). Wackestone to packstone facies with bioturbated fabric are mostly demonstrative of low energy shallow subtidal and lagoon deposition (e.g., Wilson, 1975; Strasser et al., 1999; Aleali et al., 2013a; Hajian Barzi

et al., 2015). Development of micritic envelopes exhibits low sedimentation rates and microbial organisms activities (Friedman et al., 1971; Perry, 1999; Palma et al., 2007; Flugel, 2010).

The presence of green algae suggested good aeration and light penetration (e.g., Zhicheng et al., 1997; Flugel, 2010). The existence of mud nature and peloid grains, abundant benthic foraminifers, green algae and gastropods indicates a very shallow subtidal (lagoon) setting (e.g., Purser, 1973; Bachmann and Hirsch, 2006; Flugel, 2010). A similar inner ramp facies association was reported from moderate to low energy lagoon in the Sarvak Formation (e.g., Taghavi et al., 2006;

Ghabeishavi et al., 2010; Rahimpour-Bonab et al., 2012 a, 2013; Asadi Mehmandousti et al., 2013; Mehrabi and Rahimpour-Bonab, 2014; Mahdi and Aqravi, 2014; Mehrabi et al., 2015).

Mid Ramp Facies Association

MF4: Rudist framestone/boundstone

Rudist boundstone (mounds and biostromes) are most common in the middle part of Sarvak Formation in the study area. The main constituent of this facies is rudist (specially radiolitidae rudist) which encompasses the whole thin section surface. The space between rudist frameworks has been filled by micrite (internal sediments). A rudist fabric shows packed texture in this facies. Based on James (James, 1984), rudist packed texture corresponds to rudist boundstone, rudist bafflestone or rudist rudstone. The finely granular or granular cement filled the pores or replaced some dissolved pieces of rudist debris and parts of rudist framework internally neomorphosed to microcrystalline calcite. This facies formed the core of lenticular mounds and build-ups, few meters to 10 m high, which located in the margin of platform (Flügel, 2010). Radiolitidae rudist in this facies shows reticulate fabric caused by the calcitic cellular prismatic layer (Flügel, 2010) (Fig. 5d).

MF5: Rudist debris grainstone

The main feature of this grain-dominated facies is indicated by the abundance of rudist debris (mostly radiolitids), as compared to the other constituents. Rudist fragments comprise 40 to 65% of the grains and demonstrate variation in size. Other bioclast similar to shell fragments and benthic foraminifera represent only less than 15% of the total grains. Peloids and intraclasts are relatively scarce (< 5%). This facies is marked by presence of grain-supported fabric, well-rounded bioclast fragments, and poor to moderate sorted (ranging in size from 500µm to 3mm). The matrix is coarse sparry calcite, rarely micritic and most of the skeletal grains are mostly coated by a micritic envelope, with the interior filled with spatic microcrystalline calcite (Fig. 5e).

MF6: Rudist debris bioclast grainstone

This grainstone is characterized by the plenty of rudist debris and shell fragments. This microfacies is represented by grain-supported texture (grainstone), absence of mud and large size bioclasts fragments. The main skeletal constituents are rudist debris, bivalve shells, bryozoans, echinoderms and coral debris. Grains are coarse in size (mainly up to 1.5 mm) and well-sorted (Figs. 5f and 6a).

MF7: Rudist debris floatstone/rudstone

This facies comprises of larger than sand size rudist debris, which are embedded or floated in fine-grained lime matrix (micritic mudstone). The grains are mainly derived from the devastation of reef builder frameworks, especially rudist skeletons. Rudist fragments range in size from 0.5–2.5 mm thick and 0.75–5 mm length. They represent 10–40% on average, and exceptionally 60%. Benthic foraminifera, bivalves and echinoid/crinoids shells are also present as subordinate components of this facies. Most of the skeletal grains, especially rudist debris and echinoderm fragments exhibit a thin micritic rim. Emery and Klován (1971) are introduced this facies after Dunham (1962) classification, it composed of self-supporting large grains (more than 2mm thick) surrounded by fine matrix of lime mudstone (Fig. 6b).

Environment interpretation

Rudist framestone/ boundstone facies (MF4) forms as isolated barrier/biostrome island-shoal with low-relief feature similar to the coppice at the margin of platforms and in this article used the term build-up to describe them.

Facies 5 and 7 indicated fragmentation of rudist happened under circumstances of irregular storm events and/or intensive bioerosion and indicated that the build-up has been destroyed before creating the wide colonize. These fragments create rudist debris sediments that were extended to the different parts of mid-ramp. Sadooni (2005) believed that Rudist barriers were eroded continuously during deposition whilst the basin was shallowing-up to wave base. Based on Wilson (1975) these facies are formed in forereef setting where the powerful waves and currents action are predominant. Rudist conglomeritic floatstone has applied by Alsharhan and Nairn (1993) to describe lime wackestone in the Middle Cretaceous rudist bearing carbonate (Mishrif Formation) in Persian Gulf.

The rudist barriers are discontinuous and separate by channels. The grain supported nature and lack of mud, well-sorted bioclastic grainstones, mixture of the benthic and planktonic fauna indicated that facies 6 is part of a high-energy and turbulent channels located in the proximal to middle parts of the mid-ramp. Rahimpour-Bonab et al. (2013) and Mehrabi et al. (2015) interpreted these facies as patch reef taluses and mid-ramp channel facies.

Records of this facies association of the Arabian Peninsula and Zagros basin have been documented by several authors (e.g., Alsharhan, 1995; Aqravi et al., 1998; Sadooni, 2005; Taghavi et al., 2006; Cross et al., 2010; Ghabeishavi et al., 2010; Rahimpour-Bonab et al., 2012a, 2013; Aleali et al., 2013; Mahdi et al., 2013; Mahdi and Aqravi, 2014; Esrafil-Dizaji et al., 2015).

Outer Ramp and Basin Facies Association

MF8: Peloid bioclastic packstone

This facies is a transitional facies between mid ramp and outer ramp, in which mid ramp components such as small rudist debris and benthic foraminifer are located next to open marine components (pelagic fauna). The bioclastic content is mainly composed of small rudist debris, bivalve and echinoids/crinoids fragments, calcareous sponge spicules, planktonic foraminifera (such as globigerina) and oligostegina, accompanied by smaller quantities of benthic foraminifera. Peloid grains also are visible. The allochems are dispersed in bioturbated micritic matrix (Fig. 6c).

MF9: Oligosteginid wackestone/packstone

This wackestone to packstone is characterized by the abundance of oligosteginids together with infrequent planktonic foraminifera, echinoid fragments, ostracods, tiny rudist debris and scarce peloids (Fig. 6d). The matrix is micrite with important fractures. In some cases, Glauconitization and phosphatization are also visible.

MF10: Planktonic foraminifera wackestone/packstone

This microfacies is micritic mud rich facies with lacks of shallow subtidal fauna. Non-keeled planktonic foraminifera (such as Globigerinoides, hedbergellides, etc.) are the common skeletal constituents that are immersed in a micritic matrix. Oligosteginids, thin bivalve

Figure 6. Photomicrographs of the main carbonate microfacies types of the Sarvak Formation. (a) MF6: Rudist debris bioclast grainstone. (b) MF7: Rudist debris floatstone/rudstone. (c) MF8: Peloid bioclastic packstone. (d) MF9: Oligosteginid wackestone/packstone. (e) MF10: Planktonic foraminifera wackestone/packstone. (f) MF11: Microbioclastic mudstone/wackestone.

shell, ostracods and very small peloids are Subordinate constituents. Deposition took place below both storm wave base and light penetration zone. (Fig. 6e).

MF11: Microbioclastic mudstone/wackestone

This microfacies characterized by mud dominated matrix and abundant silt size components such as planktonic foraminifer, oligosteginids and very thin shell fragments. Other major features are lacks a shallow-water neritic fauna, presence of anoxic minerals and calcite filled microfractures. This facies is deepest microfacies of the Sarvak Formation (Fig. 6f).

Environment interpretation

The thickest interval of the outer ramp and basin deposits is present in the lower part of the Sarvak Formation (lower Sarvak) and is approximately 250 m thick (Fig. 3b). MF8, 9 and 10 are belong to outer ramp and MF 11 is belong to basin sub-environment. Absent of wave and flow structure, high amount of lime mud, mud-dominate texture, lack of large amount of shallow-water neritic (benthic) fauna and large skeletal fragments and abundance of planktonic foraminifera suggest low energy, calm and deep conditions, below fair weather wave base for this facies association (Wilson, 1975; Buxton and Pedley, 1989; Reading, 1996; Flugel, 2010). According to Omidvar et al.

(2014) abundance of planktonic fauna demonstrated deeper and more pelagic conditions. The dominance of non-keeled pelagic foraminifers and calcispheres (Oligosteginids) implies eutrophic conditions (Luciani and Cobianchi, 1999; Aguilera-Franco and Hernández Romano, 2004). The low energy hydrodynamic regime evidences in this facies association implies a deposition below the normal wave base (Wilson, 1975; Read, 1985; Tucker, 2001; Flugel, 2010; Geel, 2000). A similar these microfacies (MF8 to MF11) was reported from outer ramp to basinal low-energy, deep subtidal (e.g., Alsharhan, 1995; Asadi Mehmandousti et al., 2013; Mehrabi and Rahimpour-Bonab, 2014; Mahdi and Aqrabi, 2014).

Depositional Environments

Microfacies and depositional setting analysis of the Sarvak Formation (and its equivalents) in various parts of Zagros basin and Arabian Peninsula have been antecedently studied by many authors. Some of studies implicated that Sarvak Formation was deposited in a wide carbonate ramp platforms (e.g., Aqrabi et al., 1998; Rahimpour-Bonab et al., 2012a, b, 2013). On the contrary, some other examples demonstrated that Sarvak Formation was formed in rimmed shelf system

(e.g., Alsharhan and Nairn, 1993; Alsharhan, 1995; Sadooni and Alsharhan, 2003; Taghavi et al., 2006). Ghabeishavi et al. (2010) distinguished 12 microfacies types formed on a shallow carbonate shelf setting in the SW of Iran (Zagros basin). Asadi Mehmandosti et al. (2013) proposed Sarvak Formation in Izeh Zone comprised of four facies groups including open marine, shoal, lagoonal and tidal flat, that formed in a ramp-type platform in the middle Cretaceous. Mahdi and Aqrabi (2014) and Mehdi et al. (2013) mentioned that Mishrif Formation (Sarvak equivalent) in southern Mesopotamian Basin of the Iraq was formed on a Rimmed carbonate platform. According to Rahimpour-Bonab et al. (2012), Mehrabi and Rahimpour-Bonab (2014) and Mehrabi et al. (2015) Sarvak Formation was developed on the a homoclinal ramp-type depositional regime of the humid tropical climate and abundant rainfall.

On the basis of sedimentologic and petrographic criteria, facies types and distributions, and lateral and vertical arrangement of facies associations, it could be mentioned that the Sarvak Formation in the studied area, formed on the carbonate ramp like platform with gentle slope.

In middle part of this ramp, rudist build-ups separated the platform interior from the deep marine and basin environments (Fig. 7). These rudist build-ups are located in shallow marine mid ramp, near the fair

Figure 7. Schematic diagram showing a ramp platform depositional setting reconstructed for the Sarvak carbonates succession in the study area. Three facies associations identified in this environment are juxtaposed along the inner ramp to basin as shown in schematic cross section. Distribution of facies and carbonate particles and sedimentary characteristics are shown on the model.

weather wave base (FWWB) and continuously were eroded by high-energy waves and currents (Fig. 7). Destroyed fragments of rudist build-ups dispersed over a wide area and created rudist debris bearing facies (MF3, 5, 6 and 7). Tucker (2001) and Flugel (2010) introduced barrier system ramp depositional model with isolated barrier island-shoal. Scott (1990) claimed that on the shelf margins, ramps, and atolls of the middle Cretaceous, rudists and corals formed “true reefs,” and that within carbonate shelves, and on high-energy shelf margins, rudist-dominated associations formed reef mounds and biostromes (Kauffman and Johnson, 1988; Scott, 1990; Skelton and Gili, 1991; Gili et al., 1995; Hernandez, 2011). Sanders (Sanders, 1996; Sanders, 1998) suggested the term rudist formations for all rudist bearing lithologies, irrespective of any other connotations. Ross and Skelton (1993) believed that rudists prevalently created biostromes/reefal barriers (especially in cretaceous age) at the margins of carbonate platforms. Previous works show that in many fields in the Middle East, the rudist bearing reservoirs mainly composed of rudist build-ups (bafflestone and boundstone) and/or rudist debris bearing facies such as grainstone and floatstone (e.g., Alsharhan, 1995; Aqrabi et al., 1998).

Rudist build-ups did not form continuous barrier reef with barred

nature and they arranged like island chain. The presence of benthic foraminifera (such as miliolid) associated with planktonic microfacies is the credible evidences for absence of any continuous and uninterrupted bioclastic barriers / barrier reef in depositional setting (currents removed benthic foraminifera to deeper parts of platform). According to facies characteristics, distribution of the bioclast remains and relationship between facies three major facies association recognized in the middle Cretaceous succession in the study area. These contain inner ramp, middle ramp, outer ramp and basin (Figs. 7, 8b, 9).

Bioturbated wackestone to packstone facies, abundance of benthic foraminifera and peloid, strong bioturbation and micritization interpreted to have deposited in the restricted inner ramp (restricted lagoon) settings with slight connection with the mid ramp (Figs. 7 and 8b; MF: 1–3). Middle ramp deposits are interpreted based mainly on grain-supported texture (allochemical nature), high abundant rudist debris, roundness and large size grains (Figs. 7 and 8b; MF: 4–7). The outer ramp and basin settings are characterized by high frequency of planktonic foraminifera and oligosteginid contents inserted in mud-dominated sediments (Figs. 7 and 8b; MF: 8–11).

Detailed frequency analysis of facies indicated that outer ramp and

Figure 8. (a) Schematic sketch showing idealized third-order sequence model. The Sarvak Formation sequences are generally composed of rise hemisequence with deepening upward trend and fall hemisequence with shallowing upward trend. (b) Pie Diagram showing the proportion of facies associations (sub environments). (c) Facies percentage pie diagram, representing the percentage distribution of facies in the Sarvak Formation.

Figure 9. Sedimentological log of the Sarvak Formation on the Tang-e Solak area. Sedimentological characteristics, facies features, depositional environments and third-order sequences are shown.

basin facies associations are the most frequent facies in the study area (approximately 44 percent) (Fig. 8b). Inner ramp facies association exhibit low frequencies (around 8 percent) (Fig. 8b). This shows that deep marine conditions were mainly predominated in middle Cretaceous age, in the study area (Izeh zone). Oligosteginid wackestone/packstone (MF9) is the most frequent facies and rudist framestone/boundstone (MF4) is the least abundant facies (Fig. 8c).

Depositional Sequences

The depositional facies characteristics of the Sarvak Formation indicate a distinct number of depositional sequences, systems tract and sequence boundaries. According to the vertical distribution of the facies associations, the carbonate successions of the Sarvak Formation can be grouped into two-third order depositional sequences. This depositional sequences were deposited during middle Cretaceous age (Fig. 9) and were comprised of depositional transgressive system tract (TST) with deepening trend and highstand system tract (HST) with shallowing trend (Figs. 8a and 9). In this study, according to detailed visual observations of field study and thin sections, distribution of facies (the vertical arrangement of the facies) and stacked to form facies groups, depositional sequences were interpreted.

The concepts that advanced by many researchers were applied for sequence stratigraphy interpretation (e.g., Posamentier et al., 1988; Vail et al., 1991; Van Wagoner et al., 1991; Emery and Myers, 1996; Catuneanu, 2002, 2006; Catuneanu et al., 2011). The sequence stratigraphy of Sarvak Formation (and its equivalents) has been documented in the previous study (e.g., Van Buchem et al., 2006, 2011; Cross et al., 2010; Ghabeishavi et al., 2010; Razin et al., 2010, 2014; Mahdi and Aqrabi, 2014; Vincent et al., 2015). Two 3rd-order depositional sequences were denoted in the Sarvak Formation (Figs. 8a and 9) that includes:

Depositional Sequences A

The depositional sequence A formed in the lower part of the Sarvak Formation in the study area. This sequence is around 570 m thick and directly overlays basinal shale/ marl of the uppermost part of the Kazhdumi Formation (Fig. 4a). The lower sequence boundary (SB-A) is located on underlying Kazhdumi Formation and there is no evidences of subaerial exposure and sharp facies changes at the lower boundary of the Kazhdumi/Sarvak Formations. The transgressive systems tract (TST) of sequence A is mostly consist of outer ramp and basinal facies association (MF8–MF11). The TST package is characterized by packstone to mudstone texture and pelagic content (such as planktonic foraminifera) that exhibited deepening-upward trend (Fig. 9). The maximum transgression is marked by fine-laminated argillaceous mudstone/wackestone with pelagic foraminifers and oligosteginids (MF11) that was deposited under low-energy basinal conditions (Figs. 6f and 9). In the present study, define this part as maximum flooding zone (MFZ) instead of a maximum flooding surface (due to high thickness). The highstand systems tract (HST) of sequence A exhibits a gradual exchange from deep-water facies toward the Inner ramp facies and shows shallowing upward pattern. The early HST is mainly composed of outer ramp facies specially planktonic foraminifera wackestone/packstone and Peloid bioclastic packstone. The late

HST forms as progradational stacking pattern and consist of shallowing upward facies distribution from middle ramp to inner ramp. Late HST started with the deposition of grain dominated facies (packstone and grainstone) that contains of rudist debris (MF3–MF7) and continued with benthic foraminifer bearing wackestone (Fig. 9).

Depositional Sequences B

The lower part of the depositional sequence B (TST) predominately composed of mid ramp and outer ramp facies association and indicated a retrogradational stacking pattern with a deepening upward trend (Figs. 8a and 9). A development in the accommodation space is recognized by shallow inner ramp facies (Benthic foraminifera packstone/wackestone) covered by the mid ramp facies such as rudist boundstone, rudist debris grainstone and rudist debris floatstone. The maximum flooding surface that put a top on transgressive systems tract corresponds to an outer ramp facies association (Fig. 9). Peloid bioclastic packstone (MF8, Fig. 6c) with present planktonic foraminifers indicates deep-subtidal outer ramp facies and is described as the MFS. Development of grain-supported mid ramp facies such as rudist debris grainstone and rudstone represents the early highstand systems tract in sequence B.

The upper part of sequence B (late HST) chiefly is made up of the inner ramp facies association with shallowing upward trend (Fig. 8a). Bioclast rudist debris packstone/grainstone overlain by benthic foraminifera wackestone/packstone represents progradation of strata into late HST (Fig. 9). The boundary between sequence A and B is characterized by benthic foraminifera wackestone and is interpreted as a SB 2 sequence boundary, because displays no obvious evidences of subaerial exposure. The upper boundary of the sequence B is characterized by erosional unconformities, weathered surface and intense iron-oxide staining (Figs. 4b and 9).

Conclusions

The Sarvak Formation in the Tang-e Solak area can be subdivided into three large-scale lithostratigraphic units; including A, B and C units, from base to top. Based on the sedimentary features 11 representative microfacies that are organized into three facies associations from distal to proximal part of the platform including inner ramp, mid-ramp, outer ramp and basin facies associations. Facies analysis in lateral and vertical distribution indicated middle cretaceous successions was formed on a shallow carbonate ramp depositional system with rudist build-ups that separated the platform interior from the basin environment. Frequency analysis of facies indicated outer ramp and basin facies associations are the most frequent facies. In addition, on the basis of the sequence stratigraphic analysis two third-order deposition sequences are recognized. These deposition sequences are composed of depositional transgressive system tract (TST) with deepening trend and highstand system tract (HST) with shallowing trend.

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Seyed Mohsen Aleali is an Assistant Professor of sedimentary and sedimentary petrology in the department of geology at the Science and Research branch of Islamic Azad University, Tehran, Iran. His research focuses on microfacies and diagenesis analysis, depositional setting, sequence stratigraphy and reservoir quality studies in the carbonate systems.