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Sequence stratigraphic analysis and sea-level history of the Upper Jurassic deposits (Mozduran Formation), south of Aghdarband, NE Iran

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ABSTRACT

The Kopet-Dagh Basin is a large sedimentary basin in northeastern Iran that host the giant Khangiran and Gonbadli gas fields. The Mozduran Formation with its various sedimentary facies is an important reservoir widely distributed in the basin. A sedimentological analysis of Upper Jurassic Mozduran Formation resulted in an accurate reconstruction of the sedimentary environments and the sequence stratigraphic framework south of Aghdarband. The strata consist of six different facies associations including 12 carbonate, one evaporate and two siliciclastic subfacies. On the basis of their various components, structural and textural characteristics, these facies were deposited on a homoclinal ramp in tidal flat to open marine environments ranging from supratidal to subtidal settings. Facies A1 and A2 represent open marine, B1-B4 Shoal, C1-C4 lagoonal and D1, D2, E, T1 and T2 tidal flat and Salina environments. In addition, based on detailed field and laboratory studies on the facies architecture, several large-scale (long-term) depositional sequences could be distinguished in the stratigraphic sections of the study area. These sequences are composed of LST, TST and HST that are separated by a SB1 and SB2 sequence boundaries. The paleogeography of the study area during the Late Jurassic time is reconstructed in five block diagrams.

Introduction

The Kopet-Dagh Basin NW-trending in northeastern Iran (Figure 1(A, B)) contains in the eastern part with about 7000 m of carbonate, siliciclastic and evaporate sediments that were deposited from Jurassic through Miocene time (Afshar-Harb 1979, 1994) and separates central Iran from Eurasia (Turan platform). The thickness of these sediments in Turkmenistan may have reached up to 15000 m (Lyberis et al. 1998). Five major transgressive and regressive sequences have been documented in the eastern part of the basin, and the subsidence rate has been estimated as about 98.2 m per million years (Moussavi-Harami and Brenner 1992). The Kopet-Dagh Basin formed in the Middle Jurassic in an extensional regime after northeastern Iran collided with the Turan Plate as the eastern extension of the South Caspian Basin (Taheri et al. 2009). As a result, subsiding basin formed along longitudinal faults (Afshar-Harb 1979; Berberian and King 1981; Alavi et al. 1997; Ruttner 1993; Garzanti and Gaetani 2002) (Figure 2).

After closure of the Paleotethys, thermal subsidence reached its maximum in the Jurassic. Following these tectonic events, sedimentation started in mid-Jurassic times with deposition of the fluvo-marine conglomerates, sandstones and mudstones of the Kashafrud Formation which reaches a thickness of about 2 km (Poursoltani et al. 2007). Following a marine transgression in Late Bajocian and Bathonian (Fürsich et al. 2009), carbonate deposits of the Mozduran Formation overlie the Kashafrud Formation and sedimentation continued through the Late Jurassic and probably Neocomian time. These carbonates unconformably underlie continental siliciclastic sediments of the Shurijeh Formation (Figure 3). In this paper, four stratigraphic sections have been selected in Kopet-Dagh Basin for determination depositional environments, sequence stratigraphic framework and paleogeography of the Upper Jurassic Mozduran Formation.

Material and methods

In this study, four stratigraphic sections have been measured in Shirab 1, west of Kol-e-Malekabad, Shirab 2 and Kale Shahmohammad. About 400 thin-sections have been prepared for petrographic studies. The sections were measured using a hand level, Jacob staff, and tape and sampled. Features observed included: unit thickness, unit content (skeletal and non-skeletal grains), sedimentary structures, textures (i.e. grain size, sorting, and roundness), and unit contacts. For identification of dolomite and calcite mineralogy and ferroan and non-ferroan crystals, thin-sections were stained with Alizarin-Red S and potassium ferricyanide (Dickson 1965, 1966). The grains and matrix contents were measured by using percentage charts (Flügel 2010). Carbonate facies nomenclature is based on Dunham’s (1962) classification. Identification of depositional sequences and sea-level changes were interpreted based on the studies of Carozzi (1993), Van Wagoner et al. (1988, 1990), Schlager (2003), Catuneanu
The facies are based on grain type (skeletal and non-skeletal), grain size, matrix and sedimentary structures.

**Open marine Facies Association A**: including two A1 and A2 subfacies

**Subfacies A1**: Bioclast-packstone with brachiopods (20%) and echinoderms (20%). Other bioclasts such as bryozoans and bivalves are rare (about 1%). Non-skeletal grains are intraclast (8%). Detrital grains (quartz) are rare in this subfacies (1%). Cement is mostly micrite and locally blocky and syntaxial spary calcite (Figure 4(A)). The allochems are well sorted.

**Subfacies A2**: Bioclast-grainstone with brachiopods. The main allochems in this facies are skeletal grains such as brachiopods (20%) and bivalves (15%). Non-skeletal allochems include ooids (5%), intraclasts (1%) and detrital quartz (5%) which are rare.

et al. (2009, 2011, 2013). These sequences have been correlated with those of Haq et al. (1988). The depositional history of the study area has been presented in five block diagrams.

**Facies analysis and depositional environments**

The Mozduran Formation displays a variety of lithologies and thickness variations in the studied sections. These sections are mainly composed of limestone, sandstone, shale and evaporites (gypsum). The deposits consist of various microfacies representing different environments with different energy and flow regimes. Based on petrographic studies six facies associations (A-E and T) including 15 carbonate (A-D), one evaporate (E) and two siliciclastic subfacies (T1 and T2) have been distinguished. The facies are based on grain type (skeletal and non-skeletal), grain size, matrix and sedimentary structures.

**Open marine Facies Association A**: including two A1 and A2 subfacies

**Subfacies A1**: Bioclast-packstone with brachiopods (20%) and echinoderms (20%). Other bioclasts such as bryozoans and bivalves are rare (about 1%). Non-skeletal grains are intraclast (8%). Detrital grains (quartz) are rare in this subfacies (1%). Cement is mostly micrite and locally blocky and syntaxial spary calcite (Figure 4(A)). The allochems are well sorted.

**Subfacies A2**: Bioclast-grainstone with brachiopods. The main allochems in this facies are skeletal grains such as brachiopods (20%) and bivalves (15%). Non-skeletal allochems include ooids (5%), intraclasts (1%) and detrital quartz (5%) which are rare.
compared to skeletal allochems. Dolomite replacement has been observed in some allochems such as intraclasts and echinoderms and rarely in the margin of ooids. Intergranular cement is as granular or blocky (Figure 4(B)). Clasticity index of quartz, intraclasts and echinoderms is 0.4, 1 and 0.8 mm respectively. This facies is medium-to thick-bedded and buff to grey color in the outcrop.

**Interpretation (Facies Association A):** Allochems are mostly brachiopods, echinoderms, bivalves and bryozoans. These faunal elements are stenohaline and carried out to open marine conditions (Wilson 1975; Tucker and Wright 1990; Sanders and Hofling 2000; Echnider et al. 2004; Flügel 2010). Most of middle and outer ramp sediments deposited in the photic zone typically are composed of crinoids, brachiopods, bryozoans and bivalves (Burchette et al. 1990; Bai et al. 2017). Non-skeletal allochems in this facies consist of low amounts of ooids and intraclasts which were probably transported by currents to this environment. Horizontal lamination and occasionally cross-lamination are present, indicating deposition may have taken place in relatively low to medium-energy in the open marine environments. The absence of hydrodynamic structures in some parts suggests a permanent low-energy environment probably located below the storm wave-base (SWB) (Brigaud et al. 2009). The facies belong to Wilson’s (1975) fifth facies belt to Irwin’s (1965) X facies belt. The depositional environment of this facies is comparable with recent environments such as the Persian Gulf and Shark Bay (Alsharhan and Kendall 2003).

**Barrier Facies Association B:** This facies consists of subfacies B1–B4 that were separated based on allochem type and abundance as follows:

**Subfacies B1:** Sandy bioclast-ooid-grainstone. This subfacies is mostly composed of ooids (35%) and bioclasts (20%). Ooids are large and ranges between 0.5 and 1.5 mm with distinct concentric structure. Quartz frequency is about 10% to 25%. Skeletal grains are brachiopods (10%), echinoderms (5%), bivalves, bryozoans and others (6%). Intraclasts form about 10% of grains. Clasticity index of ooids, intraclasts, echinoderms and quartz is 0.6, 2, 1.5, 0.3, and 0.5 respectively (Figure 4(C)). They are pale to grey in color and medium to thick-bedded.

**Subfacies B2:** Intraclast grainstone. In this subfacies intraclasts dominate (60%) and ooids and bioclasts are about 10 and 5% respectively. Detrital grains are mostly quartz and form about 5% of total grains. Most grains are about 0.1 to 0.2 mm in diameter (Figure 4(D)).

**Subfacies B3:** Intraclast-oolith-grainstone. Ooids and intraclasts are main grain in this facies and their abundance is about 30% and 25% respectively. Few skeletal grains are present and consist of bivalves (2%), echinoderms (1%) and gastropods (1%). Clasticity index of ooids, echinoderms and intraclasts is 0.6, 0.5 and 0.8 respectively. These grains show relatively well sorting (Figure 4(E)). This subfacies is more common in the W of Kol-e-Malekabad and Kal-e-Shahmohammad sections and are thick-bedded, and grey with cross-bedded.
Subfacies B4: Sandy ooid grainstone. The ooids in this subfacies are more common than other grains (50%). They are mostly rounded and concentric. Composite ooids with nuclei of two or three small ooids are present. The nuclei of most ooids in this facies are quartz grains, bioclast fragments (brachiopods, gastropods, bivalves and occasionally milliolid), Other allochems are brachiopods (4%), echinoderms (3%), bivalves (3%) and bryozoa (1%). Green algae and gastropods are very rare in this subfacies (<1%). Intraclasts are about 10% and quartz grains about 12% (Figure 4(F)). Clasticity index of ooids, intraclasts, echinoderms and quartz is 0.7, 0.5, 0.8, and 0.4 respectively. Dolomite replacement of allochems was observed.

Interpretation (Facies Association B): These subfacies contain both skeletal (echinoderms, brachiopods and bivalves) and non-skeletal (ooids, intraclasts and a few peloids and aggregate grains) allochems. Relatively high amounts of stenohaline fauna (such as echinoderms and brachiopods), ooids and intraclasts and cross-bedding in subfacies B1 show that these subfacies may have formed on the seaward face of a barrier. Abundance ooids and also intraclasts in subfacies B1 point to deposition in a high energy barrier environment. Bivalve fragments also present in this facies. The main allochems in subfacies B2 are intraclasts which are associated with sedimentary structures such as cross-lamination. They indicated that this subfacies may have formed on a high energy barrier and in channels created by tidal currents (Adabi and Rao 1991). Subfacies B3 and B4 also contain ooids and intraclasts that formed on a high energy barrier (Sanders and Hofling 2000; Harris et al. 2010; Aghaei et al. 2013; Purkis et al. 2014; Pomar et al. 2015; Andrieu et al. 2017; Bai et al. 2017). Ooid-bearing facies also been reported from the east coast of Abu Dhabi (Alsharhan and Kendall 2003). Presence of ooid-bearing subfacies with cross-bedding evidenced their formation in warm,
shallow, and saturated to supersaturated water with respect to calcium carbonate (Betzler et al. 1997; Burchette et al. 1990; Purkis and Harris (Mitch) 2016). Concentric ooids are related to their aggradational growth in areas subject to tidal currents. Detrital grains that are mostly quartz are abundant in many subfacies and reflect a variety of processes such as shore currents, occasional storms and also tectonic activities (Garber 1980; Burchette and Wright 1992; Martin-Chivelet et al. 1995; Cooley and Read 2004; Yilmaz et al. 2016). The presence of different amounts of detrital grains in most of the samples indicate a close source area (Miall 1997; Amir Hassan et al. 2013). Facies with ooids, bivalves and detrital quartz mostly belong to the inner ramp. The west margins of central Florida represent a similar inner ramp facies with ooids, bivalves and detrital quartz (Ginsburg and James 1974). Based on comparison with similar facies, grainstones with bivalve, echinoderm and bryozoan fragments probably formed at the depth of about 30 to 100 m (Nelson et al. 1988; James et al. 2001; Pomar et al. 2001). Intraclast grainstones probably belong to ramp slope (Burchette et al. 1990; Aghaei et al. 2013; Bai et al. 2017). The coast of Abu Dhabi also displays inner ramp ooid-grainstones. Good sorting of allochems and a relatively high clasticity index indicate high energy conditions during their deposition. Additionally, the existence of lamination, cross-lamination and ripple marks also suggest the high-energy character of these facies. Similar facies are recently forming in Abu Dhabi and the Persian Gulf (Alsharhan and Kendall 2003). These subfacies are similar to the sixth facies belt of Wilson (1975) and belong to the Y zone of Irwin (1965); high energy, oxygen-rich environments with high amounts of nutrients above the fair-weather wave base. The Persion Gulf coast is a recent example of ramp formation (Purser 1973). Similar environments are found, for example in West Florida, Yucatan Bay, Shark Bay and Bahama Bank (Alsharhan and Kendall 2003).

Lagoonal Facies Association C: These subfacies differentiated based on the type and abundance of allochems and matrix (C1-C4).

Subfacies C1: Sandy bioclast-packstone with ooids. Skeletal and non-skeletal grains constitute about 50%. Skeletal allochems (25%) consist of bivalves (15%), red algae (5%), brachiopods (2%), echinoderms (1%) and gastropods (1%). Non-skeletal allochems mostly consist of ooids (20%) and some intraclasts (5%). Quartz grains are very rare (1%). The space between grains is filled with lime mud which partially neomorphosed to microspar and spar (Figure 5(B)).

Subfacies C2: Ooid-packstone. Ooids are the main allochem in this subfacies (50%). Other allochems consist of intraclasts and bioclasts. Bioclast fragments consist of bivalves, miliolids and gastropods. Peloedoids are about 1%. Micritization affected ooids and destroyed their internal structures. Micrite is filled the space between allochems (Figure 5(A)).

Subfacies C3: Peloid-packstone. Peloids are the main components of this subfacies (60%). They were affected by neomorphic processes and changed to microspar and sparry calcite (Figure 5(C)). This subfacies is thin to medium-bedded and grey to pale in color in the field. Distinct dissolution features have been observed on a bedded surface in the field.

Subfacies C4: Ostracod mudstone. This subfacies is mostly composed of lime mud and dispersed ostracod fragments (10%). In addition to bioclast fragments, gypsum occurs. This subfacies, grey to light grey in color, is interbedded with gypsum beds about 30 cm in thickness in the outcrop (Figure 5(D)).

Interpretation (Facies Association C): Various allochems such as peloids, ostracods, green algae, miliolids and gastropods and also high amount of lime mud with scattered evaporite minerals indicate that these subfacies formed in a quiet, low energy environment, away from wave influences. Peloedoids are rounded, well sorted and mostly of fecal origin. Ostracods live in various environments ranging from fresh water to hypersaline (e.g., Flügel 2010). Based on these features these subfacies characterize a restricted lagoon (Al-Wosabi and Al-Aydrus 2011; Turi et al. 2011; Zamannejad et al. 2013). In addition, fekal pellets may be attributed to warm, shallow, and supersaturated water with respect to CaCO3 in the environment with restricted circulation (Scoffin 1987; Adabi and Rao 1991). In these carbonate lagoons generally fine sediment accommodated and in many cases was accompanied by a restricted fauna. Variations in these environments are related to water circulation, which was mostly controlled by tidal currents and climate. Peloids and aggregates form in low-energy shallow-water environments such as lagoons and bays. These subfacies based on their components and lack of storm and high-energy currents structures attributed to restricted inner ramp environment (Burchette et al. 1990; Betzler et al. 1997; Adachi et al. 2004; Aghaei et al. 2013; Yilmaz et al. 2016; Andrieu et al. 2017; Bai et al. 2017). These facies belong to facies belt 7 of Wilson (1975) characterized by salinity values differing from open marine conditions and absence of stenohaline fauna. Based on Erwin (1965) model this facies belong to Z zone. These facies form in modern environments such as the Persian Gulf and Bahama Bank (Alsharhan and Kendall 2003).

Tidal Flat Facies Association D: Based on petrographic features, this facies can be subdivided in two subfacies, D1 and D2.

Subfacies D1: Mudstone. There are no allochems in this facies. Dissolution features and sedimentary structures such as lamination occur. The rocks are thin to medium-bedded and grey to buff in color in the outcrop (Figure 5(E)).

Subfacies D2: Dolostone. Fine to coarse crystalline dolomite is commonly observed in the studied sections (Figure 5(F)). Coarse crystalline dolomites mostly are secondary and formed during burial diagenesis and under the influence of Mg-rich fluids. Primary dolomites are fine-crystals and can be formed in low temperature environment (Gregg and Sibley 1987). Diagenetic dolomites are mostly planar (with relatively well developed crystal face and sharp boundaries) including planar-S, planar-A and planar-E. They are thin-bedded and of buff-color with evaporite interbeds.

Interpretation (Facies Association D): These fine-grained mudstones and dolostones, along with the lack fossils can be related to a supertidal sabkha environment. The lack of fossils in this facies indicates restricted circulation of water and the absence of appropriate conditions for organism growth (Warren 2000; Yechiel and Wood 2002; Alsharhan and Kendall 2003; Al-Wosabi and Al-Aydrus 2011; Aghaei et al. 2013; Zamannejad et al. 2013). These subfacies belong to facies zone 8 and standard microfacies 22 of Wilson (1975), deposited on a restricted low-energy platform.

Evaporite Facies Association E: Gypsum. This facies is relatively widely exposal in W of Kol-e-Malekabad and Shurab 1 with a thickness of about 90 and 11 m respectively. There are
Interpretation (Facies Association E): This facies is mostly composed of gypsum and formed in a hypersalina environment (Zamannejad et al. 2013). Ostracod mudstone and interbeds of grey to red colored lime mudstone and shale. These lime mudstone interbeds are unfossiliferous except with a few scattered ostracods (Figure 5(G)).
marl interbedded with gypsum indicate that they formed in a supratidal restricted environment (Warren 2000). In peritidal environments salinity may seasonally vary because freshwater influx during humid seasons. A similar example is the Upper Jurassic evaporite facies occurring in the southern England (Strasser and Davaud 1983). Based on Warren's (1999) classification, primary evaporites are depositional, forming due to sunlight evaporation. As the Late Jurassic climate in the eastern Kopet-Dagh Basin was warm and dry with temperature about 24–29 °C (Adabi and Rao 1991; Mahboubi et al. 2010), the evaporite minerals of the Mozduran Formation formed in an arid climatic conditions. Additionally, high amounts of evaporites in the Baghak and Padheh sections (Afshar-Harb 1973) in the north of the study area and also in the studied sections (Shurab 1 and B, W of Kol-e-Malekabad and Kal-e-Shahmohammad) suggest that deposition of the Mozduran evaporites may have taken place in the salina with wide extension along the eastern Kopet-Dagh Basin during the Late Jurassic. Similar carbonate and evaporite associations are present in the United Arab Emirates and Mesozoic and Tertiary strata of the Persian Gulf.

Siliciclastic Facies Association T: This facies can be subdivided into a fine and medium-grained subfacies.

**Fine-grained subfacies (T1):** Shale. This subfacies occurs as interbeds in different parts of the sections. These are grey, dark grey to red, unfossiliferous, shales. Gypsum crystals are distributed in some part of these shales (Figure 5(H)).

**Medium-grained subfacies (T2):** Sandstone. Sandstones are abundant in the sections studied W of Kol-e-Malekabad, Shurab 1 and B, and Kal-e-Shahmohammad (Figure 5(I, J)). Sandstone components are mostly quartz grains, less commonly metamorphic (slate and phylite) and sedimentary rock fragments and more rarely heavy minerals (zircon). The quartz grains are mostly monocrystalline with straight extinction with rare inclusions. Polycrystalline quartz is rare (2–3%) and most quartz grains are metamorphic in original, displaying orientation. Carbonate cements (calcite and dolomite) and some silica (overgrowth) and iron oxide are common cements in these sandstones. These sandstones are moderately to well-sorted and subangular to rounded. Bent mica (muscovite) are present in grain margins. Size of quartz grains ranges between 0.1 and 0.6 mm and rock fragments is less than 0.2 mm. Quartz grains in some samples are about 97% and most of them are monocrystalline. The rock fragments mostly metamorphic and sedimentary constitute about 10%. These sandstones subdivided into two subfacies:

1. **Quartzarenite:** Quartz grains are about 97%. The quartz grains are mostly monocrystalline with straight extinction. Polycrystalline grains are very rare (1–2%) and probably have been destroyed based on their lower mechanical durability. Rock fragment are rare (2–3%). Cement is very low in this facies and mostly carbonate (calcite and dolomite). Silica cement present as overgrowth. Sedimentary structures such as lamination, bimodal-bipolar cross-beds and symmetrical ripples are present in this subfacies.

2. **Sulisparite:** This subfacies is common in the study area. Rock fragments are sedimentary (shale) and metamorphic (slate and phylrite) and they account for about 15%. This subfacies is mostly cemented by carbonate (calcite and dolomite) and silica (overgrowth). Quartz grains are monocrystalline with straight extinction. Sedimentary structures are relatively similar to Quartzarenites subfacies but lamination has more frequency.

**Interpretation (Facies Association T):** This facies includes two subfacies-shale and sandstone. Based on the lack of fossil, red color and interbedded of sandstone with tidal evidences and shale, they are interpreted to be deposited in coastal tidal flat area. Sandstones are mostly quartzarenites and less common sublitharenites. Quartzarenites are well sorted with moderately to well-rounded grains. High textural maturity, presence of bimodal-bipolar cross-beds and symmetrical ripples indicate that they formed in a tidal flat environment (Adnan et al. 2015; Patra and Singh 2015). Sublitharenites formed under lower energy conditions than quartzarenites documented by the preservation of rock fragments between quartz grains. Additionally, wavy and interference ripple marks and large-scale planar and trough cross-bedding indicate that such sandstones were deposited in a high-energy, wave influenced environment (Tamura and Masuda 2003).

**Depositional model**

Lack of slope facies such as deep water breccias, coral reefs and frame-building biota which produce rimmed shelves, presence of coarse-grained components such as peloids, ooids, intraclasts, carbonate bioclasts and uniform sediment production or accumulation from shallow-water to deeper water, prove that carbonates of Mozduran Formation in the study area formed on a ramp platform (e.g. Elgadi and Brookfield 1999; Brachert et al. 2001; Pomar 2001; Aurell et al. 2003; Corda and Brandano 2003; Bai et al. 2017). Generally, carbonate ramps have gentle slopes (< 1°) and there is no marked break between shallow-water agitated facies and deep marine facies (Read 1985). Therefore, based on detailed studies of Mozduran Formation, its depositional environment can be interpreted as a homoclinal ramp with tidal flat, lagoon, barrier and open marine facies. Recent homoclinal ramps such as in the Persian Gulf (Purser 1973) and Shark Bay (Logan 1974) and ancient homoclinal ramps such as the Virginia middle Ordovician ramp (Read 1980) and New York ramp (Laporte 1969) are similar to the present ramp. Facies in the sections studied mostly belong to the inner ramp (Figure 6). Based on Read's models (1985), depositional facies of the Mozduran Formation in the study area represent a ramp with an oolitic and bioclastic barrier and back-barrier deposits. These facies mostly formed on the inner ramp. Shore belt ramp facies consist of ooid and skeletal grainstones and peloids are important in this part. Mixed carbonate and siliciclastic deposits are attributed to mixing of sediments from different environments or to episodic influx of sediments from the terrestrial source (Duncan et al. 2003).

**Sequence stratigraphy**

Depositional sequences, particularly small scale (fourth-order) cycles may be influenced by both allocyclic and autogenic processes (Catuneanu and Zecchin 2013). Allocyclic (allogetic) factors are those external to the depositional system, such as eustasy, tectonics and climate whereas autocyclic (autogenic)
Depositional sequences

Based on the sedimentary facies, two long-term 3rd order depositional sequences have been distinguished in Kal-e-Shahmohammad and W of Kol-e-Malekabad, each of them consisting of several parasequences. These parasequences include carbonate facies (lagoon, barrier and open marine) at a time of sea-level rise and evaporite (gypsum) and siliciclastic facies (tidal flat) at a time of sea-level fall. Two type of sequence boundary (SB1) and SB2 were identified in the study successions.

Depositional sequence 1 (DS1)

In the W of Kol-e-Malekabad section, this sequence consists mostly of carbonate rocks with interbeds of shales and sandstones. The lower surface bounding, based on a distinct erosional surface with evidence of a horizon of yellowish to light brown paleosol, is SB1. At the base of this sequence, carbonate facies of the Mozduran Formation overlie grey shales of the Kashafrud Formation during sea-level rise. The upper boundary of this sequence on the basis of exposure evidences (evaporite deposits) is SB1. The thickness of this sequence which is mostly composed of ooid-grainstone, bioclast-grainstone and subordinately intraclast-grainstone, is 240 m. This sequence contains TST and HST facies, which were deposited on the Kashafrud shales during the transgression. TST is composed of sandstone, shale, ooid-grainstone and bioclast-grainstone formed in tidal flat to barrier environments. Several deepening upward parasequences have been identified in this sequence that generally reflect a rise in sea-level. Subsequently, HST parasequences have been deposited. As the Late Jurassic carbonate platform in the Kopet-Dagh Basin underwent several sea-level fluctuations, many parasequences of different thickness formed (Figures 7 and 8). In the Kal-e-Shahmohammad and Shurab 1 sections this sequence starts with LST which is mostly composed of evaporites (gypsum), gypsiferous shales and orange to red sandstones (Figure 9). These facies indicate a relative sea-level fall and temporary emersion of these areas (Emery and Myers 1996). The thickness of DS1 in the Kal-e-Shahmohammad and Shurab 1 sections is about 94 and 55 m, respectively. Following LST facies, lightly deeper water TST facies have been deposited. These facies mostly include tidal flat deposits (shale and sandstone) and barrier grainstones. The following HST deposits mostly contain tidal flat, lagoonal and barrier facies. The basal bounding surface is SB1 (Emery and Myers 1996; Aziz and El-Sattar 1997; Zand et al. 2016). Parasequence frequency in this sequence indicates high sea-level fluctuations at this time. On the basis of presented models by Warren (1999), Kendall (2003) and Sinha and Raymahashay (2004) evaporite facies of this sequence deposited in salina environment.

In the Kal-e-Shahmohammad the thickness of LST, TST and HST in this sequence is 32, 43, and 19 m, respectively. TST and HST facies contain several shallowing parasequences and are mostly composed of tidal flat shale and sandstones (T1 and T2) (Figure 9). In Shurab 1 the thickness of LST is low (11 m) and is mostly composed of evaporite (gypsum) deposits. The TST (34 m) is followed by the maximum flooding surface, a lime mudstone layer (Figure 10). HST with a thickness of about 10 m is characterized by several shallowing-upward and aggradation parasequences that indicate gradual shallowing (Emery and Myers 1996; Coffey and Read 2004). DS1 of Shurab 2, which are mostly composed of sandstones and shales, is Correlatable with DS1 in W of Kol-e-Malekabad. These deposits do not exist in the Kal-e-Shahmohammad and Shurab 1 sections and probably removed due to erosion (Figure 12). They are in place rhythmic,
interbedded and were deposited in supratidal and intertidal environments. The paleosol horizon that is present between DS1 and DS2 at Shurab 2 indicates emersion at this time and (SB1 sequence boundary). The thickness of DS1 in this section is about 45 m (Figure 11).

**Depositional Sequence 2 (DS2)**

At W of Kol-e-Malekabad this sequence is correlatable with DS2 in Shurab 2 and with DS1 and DS2 at Kal-e-Shahmohammad and Shurab 1. At W of Kol-e-Malekabad it starts with evaporites and, based on evidence of subaerial, its bounding surface with DS1 is erosional (SB1). This sequence contains LST, TST and HST systems tracts. The thickness of this sequence is about 168.5 m (Figure 8). In this sequence tidal flat, barrier and open marine facies (MFS) followed by HST facies that mostly contain shale and sandstone (T1 and T2). At the end of HST a distinct regressive occurred and siliciclastic facies of the Shurijeh Formation were deposited in fluvial environments. Based on these red siliciclastic sandstones and conglomerates (Shurijeh Formation) the sequence boundary is identified as SB1 type. At Kal-e-Shahmohammad the thickness of this sequence is about 64 m. The lower boundary of this sequence, based on lack of subaerial exposure, is SB2 (Emery and Myers 1996). The sequence starts with tidal flat facies LST; sandstone and shale followed by TST facies (shale, sandstone and ooid-grainstones). MFZ with bioclast-ooid-grainstones is containing bivalve, echinoderm and brachiopod fragments which reflect seaward shoal environments. These facies are followed by HST facies containing several shallowing-upward parasequences which are composed of tidal flat (T2) and barrier facies. The upper sequence boundary based on evidence of exposure and deposition of continental sediments of the Shurijeh Formation is SB1 (Figure 9). In Shurab 1, the thickness of this sequence is 33.5 m. The lower boundary is similar to Kal-e-Shahmohammad (SB2). The sequence is composed of tidal flat facies T1, T2 and D1 that represent TST and HST.

---

### LEGEND

<table>
<thead>
<tr>
<th>FACIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioclastic packstone with brachiopods and echinoderms (A1)</td>
</tr>
<tr>
<td>Bioclastic packstone with brachiopods (A2)</td>
</tr>
<tr>
<td>Sandy Bioclast-grainstone (B1)</td>
</tr>
<tr>
<td>Intraclast-grainstone (B2)</td>
</tr>
<tr>
<td>Intraclast-ooid-grainstone (B3)</td>
</tr>
<tr>
<td>Sandy ooid-grainstone (B4)</td>
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<tr>
<td>Ooid-packstone (C1)</td>
</tr>
<tr>
<td>Sandy bioclast-packstone with ooids (C2)</td>
</tr>
<tr>
<td>Ostacoda mudstone (C3)</td>
</tr>
<tr>
<td>Peloidal packstone (C4)</td>
</tr>
<tr>
<td>Sandstone 2 (T2)</td>
</tr>
<tr>
<td>Sandstone 1 (T2)</td>
</tr>
<tr>
<td>Shale (T1)</td>
</tr>
<tr>
<td>Mudstone (D1)</td>
</tr>
<tr>
<td>Dolostone (D2)</td>
</tr>
<tr>
<td>Gypsum (E)</td>
</tr>
</tbody>
</table>

**HST**: Highstand Systems Tracts
**TST**: Transgressive Systems Tracts
**MFS**: Maximum Flooding Surface
**SB**: Sequence Boundary

*Figure 7. Symbols used in sequence stratigraphy columns of Figures 8–12.*
LST is absent in this sequence. The thickness of TST is 11.5 m. Following TST, sea-level stillstand and shallowing are represented by 22 m of HST sediments. HST contains several shallowing parasequences that are composed of tidal flat facies (T1 and T2). This sequence is followed by regression and deposition of siliciclastic sediments of the Shurijeh Formation (Figure 10). In Shurab 2 section DS3 is correctable with DS2 of the other sections studied. The lower boundary, based on the absent of subaerial exposure is SB2. This sequence is composed of TST and HST facies. TST contains intertidal sandstones and shales. HST
includes gypsiferous shales, sandstones and occasionally dolostones that were deposited in shallower intertidal to supratidal environments. The thickness of TST and HST in this sequence is 48 m and 157 m, respectively. Following HST Shurijesh conglomerates erosionaly overlie this sequence (Figure 11).

**Sea-level fluctuations**

Carbonate platforms with various facies are sensitive indicators of relative sea-level fluctuations. Several factors influence facies stacking-patterns. These are consisting of tectonic process, glaciations, global sea level fluctuations and some other factors that control 3rd order eustatic cycles and sedimentary cyclicity during geologic times (Husinec and Jelaska 2006; Tuner et al. 2012; Catuneanu 2006; Catuneanu et al. 2007, 2009, 2011, 2013; Bai et al. 2017).

The Depositional Sequence 1 (DS1), present only West of Kol-e-Malekabad and at Shurab 2, mostly consists of limestone, shale and sandstone and is overlain by relatively thick-bedded evaporites (mostly gypsum and occasionally anhydrite) and red to orange sandstones (Figures 8 and 11). The lower bounding surface of this sequence with the Kashfrud Formation is a distinct erosional surface (TS) with yellowish to brownish color thin horizon of paleosol (e.g. Yilmaz et al. 2016; Andrieu et al. 2017). The upper boundary of this sequence, with evidence of subaerial exposure relatively high amounts of evaporites is SB1 (e.g. Emery and Myers 1996; Coffey and Read 2004). Sediment equivalent to DS1 at W of Kol-e-Malekabad and Shurab 2 are not present at the two other sections. Main factors include different depth of depositional environments, erosional processes, and low carbonate deposition in the other studied sections and a variety of local tectonic processes (Freeman 1999; Yilmaz et al. 2016; Bai et al. 2017).

The Depositional Sequence 1 (DS1), present only West of Kol-e-Malekabad and at Shurab 2, mostly consists of limestone, shale and sandstone and is overlain by relatively thick-bedded evaporites (mostly gypsum and occasionally anhydrite) and red...
of coastal plain deposits. Thus, barrier bars and coastal plain deposits may be absent in the TST (e.g. Yang 2007). Following these parasequences, HST parasequences were deposited. As the Upper Jurassic carbonate platform experienced several sea-level fluctuations, many parasequences with different thickness have been formed. Short-term shallowing upward cycles could be controlled by autocyclic and allocyclic processes (Lasemi 1995). Different factors such as tectonic events, subsidence influence the formation shallowing-upward cycles. Long-term shallowing and deepening (3rd) cycles of the Mozduran Formation can be correlated with those of Haq et al. (1988) and Hallam (1988). These cycles are probably having a tectono-eustatic origin because of lack of continental glaciation during the Late Jurassic time. Moussavi-Harami and Brenner (1992) proposed that sediment loading and tectonic is responsible for Late Jurassic subsidence in the Kopet-Dagh Basin. Generally, both tectonic and autocyclic processes are thought to produce the shallowing cycles of the Mozduran Formation. Accumulation of carbonates in the accommodation space generated by platform subsidence and relative sea-level rise resulted in thick shallowing-upward cycles.

The second sequence at W of Kol-e-Malekabad is correlatable with DS1 and DS2 in the other sections (Figure 11). Evaporite facies and signs of subaerial exposure at the base of DS2 at Shurab 1 section produced erosional SB1 sequence boundary. Evaporites and gypsiferous shales formed in a saline setting during relative sea-level fall (Emery and Myers 1996; Aziz and El-Sattar 1997; Warren 1999; Alsharhan and Kendall 2003; Sinha and Raymahashay 2004; Bai et al. 2017). The lower part of this sequence at the W of Kol-e-Malekabad that contain LST facies (evaporites, mudstone and dolostone interbeds) is correlatable with LST evaporite facies at the Shurab 1 and supratidal sandstones and shales at Kale-Shah Mohammad and Shurab 2. The sequence is mostly composed of evaporites and shallow-marine shales, sandstones and mudstones of tidal flat (supratidal-intertidal) origin. The LST facies sequence indicates regression in all sections of the study area and a vast area of the Kopet-Dagh Basin. In Kale-Shah Mohammad, and Shurab 1, DS1 contains LST, TST and HST systems tracts that are correlatable with DS2 at Shurab 2 and lower part of DS2 in W of Kol-e-Malekabad. In all sections, dolomitization mostly occurs in carbonates and siliciclastics of the TST and HST systems tracts (e.g. Tucker and Wright 1991; Tucker 1993). In this sequence, tidal flat, and barrier facies are more abundant than open marine facies which indicates the dominance of shallow-marine conditions at this time. The maximum flooding zone (MFZ) is represented mostly by intertidal to barrier and occasionally open marine facies. Following lime mudstone, shale and occasionally bioclast and ooid-grainstones from HST identified by several shallowing-upward and aggradational parasequences that indicate gradual shallowing (Emery and Myers 1996; Coffey and Read 2004; Andrieu et al. 2017; Bai et al. 2017). After shallow marine deposition, sea level rose and deeper water facies including barrier and occasionally open marine were deposited. Red color of sandstones with bimodal-bipolar cross-beds and symmetrical ripples as well

### Table 1: Depositional Sequences

<table>
<thead>
<tr>
<th>Series</th>
<th>Stage</th>
<th>Formation</th>
<th>Thickness (m)</th>
<th>Sample No.</th>
<th>Lithology</th>
<th>Depositional Seq.</th>
<th>Seq. Boundary</th>
<th>Systems Tract</th>
<th>Eustatic curves (cycles)</th>
<th>Rising Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Jurassic</td>
<td>Oxfordian Kimmeridgian</td>
<td>Tithonian (?)</td>
<td>80 m</td>
<td>22C</td>
<td>HST</td>
<td>DS 2</td>
<td>SB 1</td>
<td>MFS</td>
<td>4th-order (Short Term)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mozduran</td>
<td></td>
<td>0 m</td>
<td>1C</td>
<td>LST</td>
<td>DS 1</td>
<td>SB 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 10.** Depositional sequences at the Shurab 1 section.

![Depositional Sequences](image.png)
of tidal flat shale and sandstones during TST and HST are very abundant especially at the Shuab 1 and Kal-e-Shahmohammad. The boundary between DS1 and DS2 at Kal-e-Shahmohammad and Shuab 1 is often SB2 type based on lack of subaerial exposure. This sequence boundary is located between shallow tidal flat sandstones and shales that were deposited at the end of stillstand and during regressive phase. The red color and sedimentary structure (lamination and ripple marks) and lack of trace fossils in these sandstones indicate that they were deposited in a shallow tidal flat environment during sea-level fall. Repeated cycles with the same thickness in separate sequences of the Mozduran Formation point to sea-level fluctuation (Vail et al. 1991).

Figure 11. Depositional sequences at the Shurab 2 section.

as shale interbeds proves shallow-marine conditions. Generally, the W of Kol-e-Malekabad section was located seaward than other sections (Figure 12). This situation led to deposition of deeper facies (open marine) at W of Kol-e-Malekabad compared to shallower tidal flat and barrier facies. Abundant of bivalve, echinoderm and brachiopod fragments in this section suggest deposition in the lower and middle shoreface which belong to seaward barrier environments and were influenced by waves (e.g. Andrieu et al. 2017). These fragments were occasionally also observed at the Kal-e-Shahmohammad. Detrital grains among the bioclasts were introduced by coastal currents (Coffey and Read 2004). Shallowing parasequences that are mostly composed of tidal flat shale and sandstones during TST and HST are very abundant especially at the Shuab 1 and Kal-e-Shahmohammad. The boundary between DS1 and DS2 at Kal-e-Shahmohammad and Shuab 1 is often SB2 type based on lack of subaerial exposure. This sequence boundary is located between shallow tidal flat sandstones and shales that were deposited at the end of stillstand and during regressive phase. The red color and sedimentary structure (lamination and ripple marks) and lack of trace fossils in these sandstones indicate that they were deposited in a shallow tidal flat environment during sea-level fall. Repeated cycles with the same thickness in separate sequences of the Mozduran Formation point to sea-level fluctuation (Vail et al. 1991).
Figure 12. Correlation of the sequence stratigraphic units between the four studied sections.
Variable thickness of study sections of the Mozduran Formation could be caused by tectonic and erosion of waves and currents that moved these sediments to deeper parts of the basin (Coffey and Read 2004). At the end of HST a distinct regression occurred and siliciclastic facies of the Shurijeh Formation was deposited in fluvial environments. Finally, the Mozduran Formation was erosionaly (SB1) overlain by red siliciclastic sandstone and conglomerate of the Shurijeh Formation.

**Paleoclimate**

The Jurassic climate has been interpreted to represent a greenhouse period (Fischer 1982). However, a number of authors have mentioned transient icecaps as controls on eustatic sea-level changes during the Mesozoic greenhouse period (e.g. Price 1999; Stoll and Schrag 2000; Greselle and Pittet 2010). Adabi and Rao (1991) based on stable isotopes calculated a sea-water temperature of the Mozduran carbonates of about 25º C. Also Mahboubi et al. (2010) and Aghaei et al. (2014) based on oxygen isotopes, estimated an Upper Jurassic temperature of the Mozduran and Lar formations of the Kopet-Dagh and eastern Alborz of about 28 and 26 ºC respectively. This temperature range corresponds to tropical seas. Upper Jurassic temperature data from the Falkland Plateau suggest values in the range of 26–30 ºC (Jenkyns et al. 2002). Such a general warming fits the overall decline in oxygen-isotope ratios in Upper Jurassic belemnites and oysters from...
Europe and Russia (Jenkyns et al. 2002; Dera et al. 2011) and palynological evidence from the North Sea (Abbink et al. 2001). Palaeoclimatic variations in ancient sedimentary systems especially in carbonate factories are not easy to identify because of the interplay between different controlling factors such as eustasy, tectonics, the variety of carbonate producers, and sediment supply (Brigaud and Vincent 2013). Evaporites, salt and detrital red sediments in the Mozduran Formation show maximum temperatures in upper Malm in Jurassic (Mahboubi et al. 2010). The Jurassic time interval started with wide spread transgression in Asia and Europe. The land size of South Gondwana decreased and continental fragmentation began in the Triassic and continued into the Jurassic. Epeiric seas covered eastern, western and southern of Europe, Middle East, south China, Japan and many other areas. Desert area was very small and there is no report of ice cover. High temperature and rain has been appropriate for vegetation. The lowest sea-surface temperatures are recorded from around the Callovian–Oxfordian boundary, an interval identified in European as relatively cool, but these temperatures do not fall below 25º C (Jenkyns et al. 2012). In Jurassic shallow marine seas many organisms such as gastropods, sponges, corals, fish, bivalves, echinoderms and foraminifers lived.

Facies evolution

In the Kopet-Dagh Basin, the Mozduran Formation is the last lithostratigraphic carbonate unit in the Jurassic. These deposits are composed of subtidal, intertidal and supratidal facies. Subtidal deposits are characterized by medium to thick-bedded lime mudstone, wackestone and packstone with variable amounts of lime mud, peloids, oncoids, intraclasts, and skeletal grains. Shallow, higher-energy subtidal deposits are represented by packstones and grainstones with intraclasts, peloids, ooids, green algae, benthic foraminifers, and mollusk fragments. Intertidal and supratidal deposits are represented by wackstones packstones and occasionally grainstones and fenestral mudstones. These facies commonly has been dolomitized. The type section of the Mozduran Formation is mostly composed of massive carbonates (oolid-grainstones, bioclast-grainstones, bioclast-packstones, lime mudstone and dolostone) that toward the east changed to evaporate and detrital facies. In the study area siliciclastic (sandstones and shales) and evaporite sediments are common whereas the carbonate sediments decreased.

Conclusion

Based on investigations of four sections the following depositional model of the temporal facies changes is proposed (Figure 13):

(1) **Stage 1:** The study area was emerged and a paleosol horizon developed on top of the Kashafrud Formation in some areas.

(2) **Stage 2:** A transgression started after exposure of the upper Kashafrud Formation (paleosol) in the study area and lower part of the Mozduran Formation has been deposited. At this stage, relatively high-energy marine facies were developed. These deposits at the of the Kole-Malekbabad have a considerable thickness. The rocks are mostly carbonates containing ooids, intraclasts and bioclasts. In addition, numerous sedimentary structures occur such as lamination and cross-bedding. At this stage, tidal flat sediments were deposited at Shurab 2, but in Shurab 1 and Kal-e-Shahmohammad sedimentation did not occur or sediments were subsequently removed by erosional processes.

(3) **Stage 3:** During regression intertidal and supratidal facies (sandstone and shale) have been deposited in all sections. These wide spread facies are composed of red sandstones, unfossiliferous shales and evaporite ( gypsum) facies. Evaporites are more abundant W of Kole-Malekbabad than in other areas. This facies points to predominantly dry and warm climatic conditions during this time.

(4) **Stage 4:** During the following transgression, barrier to open marine facies (bioclast-packstone and -grainstone) were deposited W of Kole-Malekbabad and Kal-e-Shahmohammad and tidal flat shales and sandstones in Shurab 1 and B.

(5) **Stage 5:** This is the final sea-level fluctuation during the Late Jurassic time in the study area. At this stage, the sea level fall and a regression occurred, so that fluvial siliciclastic sediments of the Shurijeh Formation were deposited on the top of shales and sandstones of the Mozduran Formation.

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Disclosure statement

No potential conflict of interest was reported by the author.

References


