Sea-level change and deep sea sequence stratigraphy: A Middle Jurassic siliciclastic strata (Kashafrud Formation), NE Iran

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Abstract

The Upper Bajocian- Lower Bathonian succession in the Kopet-Dagh Basin of NE Iran represents fluvio-deltaic to turbidite deposits. The Kashafrud Formation provides an excellent opportunity to study the interplay between deep-water sedimentation and syndepositional tectonic subsidence (or uplift) in the region. The effects of these processes caused sea-level changes, variation in depositional sequences, and formation of different types of sequence boundaries. The Kashafrud Formation is recognized as a super-sequence and is overlain and underlain by type 1 sequence boundaries. Based on sedimentological analysis, twelve lithofacies and three facies associations have been identified in the Kashafrud Formation. The succession is represented by parasequences formed as part of a second order super-sequence, and a fourth order regression. The thickness variations indicate a strong influence of basin-floor topography on the location of depositional successions. High rates of sea-level fall led to the development of a limited number of major incised channels; in contrast the major thick-bedded mudstone indicates high rates of sea-level rise for prolonged periods. The interpreted sea-level curve during deposition of the Kashafrud Formation can be correlated with the world sea-level curve for the Middle Jurassic, with differences mainly related to local structural events in the basin. Tectonism, compaction and rate of deposition were the main factors that controlled the vertical facies transitions in these parasequences.

Keywords: *Kashafrud Formation, Kopet Dagh Basin, Iran, sequence stratigraphy*

1. Introduction

Here we study a sedimentary sequence in the Kopet-Dagh Basin, north-east Iran, to develop a facies architecture model for fluvio-deltaic and turbiditic sequences. Cyclicity of Upper Bajocian- Lower Bathonian (Kashafrud Formation) sedimentary rocks is still rather poorly understood, but study by Taheri et al. (2009), showed that the Kashafrud Formation strata can benefit from a sequence stratigraphy approach, allowing evaluation of the major controls of Upper Bajocian- Lower Bathonian relative sea-level change. The application of sequence stratigraphy to the Kashafrud Formation rock record encounters difficulties because of poor preservation. A limiting factor is that the some sequence boundaries are not observed in laterally extensive outcrops and interpretations are based on vertical lithofacies successions. Also, regional deformation and faults sometimes make interpretation difficult and should be taken into account. In non-fossiliferous successions, superposition of successive parasequences provides data for evaluating relative sea-level oscillations at different time scales (Mitchum and Van Wagoner 1991). Parasequences, the fundamental building blocks in sequence stratigraphy, are typically a few metres to a few tens of metres thick (Van Wagoner et al. 1990; Arnott 1995; Hampson and Storms 2003; Kari 2005). They are separated by marine flooding surfaces and record vertical stacking of laterally adjacent depositional facies that comprise systems tracts. Before crustal breakup, a 1753 m thick succession of sandstones and mudstones of the Kashafrud Formation were deposited (Poursoltani et al. 2007a). Deposition was related to the increasing tectonic flexure and regional subsidence of the lithosphere.

In this study, the sedimentary successions deposited on a proximal shelf are subjected to facies analysis at outcrop scale in order to determine depositional environments, and on this basis, parasequences and parasequence sets are defined and are assigned to a small number of sequences. This twofold approach is necessary for understanding stratigraphic evolution and cyclic sedimentation (Posamentier et al. 1988; Swift et al. 1991; Swift et al. 2003; Posamentier and Allen 1993; Posamentier and Allen 1999). Sequence stratigraphic models assume that a predictable stacking pattern of sedimentary facies and systems tracts is controlled essentially by the interaction of base-level changes and sedimentation. The Kashafrud Formation is predominantly composed of shale, sandstone and conglomerate. These sediments were deposited in a fluvio-deltaic to turbiditic environment (Aghanabati 2004; Poursoltani et al. 2007a; Taheri et al. 2009). Facies analysis and process/depositional interpretations are given in Table 1. The Kashafrud sediments provide an opportunity to study the stratigraphic development of fluvio-deltaic and turbiditic deposits under conditions of rising eustatic sea level (SL). Our approach uses sedimentology to reconstruct the

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paleoenvironments that accompanied infilling of the basin during depositional of the Kashafrud Formation in northeast Iran. The objectives of this study are: 1. Identification of lithofacies and interpretation of their depositional environments, 2. Depositional sequences delineation, 3. Sea-level history reconstruction in NE Iran.

2. Location and geological setting

The study sites are located in northeast Iran (Fig. 1) in the Kopet-Dagh Basin (Fig. 1), which formed after northeast Iran collided with the Turan Plate early in the Mesozoic (Garzanti and Gaetani 2002). This extensional basin accumulated 7 km of post-Triassic strata (Moussavi-Harami and Brenner 1992), that were uplifted and deformed during Cenozoic collisional events along the southern Asian margin (Lyberis and Manby 1999). In the eastern part of the basin, the Kashafrud Formation is Middle Jurassic (Upper Bajocian-Lower Bathonian) in age, and rests unconformably on Triassic volcanogenic sedimentary rocks (Sina Formation) or nonconformably on ultrabasic intrusive rocks (Fig. 2). The formation covers an area of hundreds of square kilometers, and represents a transition from fluvial sediments to deep-water turbidites (Poursoltani et al. 2007a; Poursoltani et al. 2007b). The Kashafrud Formation is disconformably overlain by marine carbonates of the Mozduran Formation (Oxfordian to Kimmeridgian), locally as much as 420 m thick (Lasemi 1995; Kavoosi et al. 2009). The ~2 km of Kashafrud strata in the basin were deposited within ~ 6.9 million years, based on the timescale of Gradstein et al. (2004). This rapid rate of deposition (in the order of 300 m per million years, not corrected for compaction) implies active subsidence and high rates of sediment supply during early basin filling. Subsidence and accumulation rates later decreased, with some 4 km of strata deposited during the 80 million years of the Cretaceous – a long-term average rate of only 50 m per million years.

3. Methods

The Kashafrud Formation was studied in seven stratigraphic sections east of Mashhad, where the base and top of the formation are observed. The outcrops are disposed along an approximate southwest to northeast transect over a distance of 50 km (Fig. 1). The seven sections were measured bed-by-bed for a total of 7523 m, and facies types were identified. Outcrops provide good exposure of conglomerate, sandstone, and limestone but only limited exposure of mudstone. Four hundred and fifty thin sections were studied to determine the lithofacies. Sandstones were classified using Folk (1980) scheme, and conglomerate was classified according the scheme of Boggs (1992). Field observations were used to assess the lateral extent and thickness variation of sandstone and mudstone packages. According to the Miall (2000) scheme of, classification, sandstone packages were classified in the field as well. Basal surfaces were described as planar or irregular erosional surfaces or as gradational, and the relief of erosional surfaces within packages was noted. Based on the identification of different lithofacies and interpretation of their depositional environments, the sequence stratigraphy of the Kashafrud Formation was interpreted.

4. Regional thickness variations

The formation is more than 2 km thick regionally, and ranges in thickness in the study area from 280 m at Agh-Darband to 1753 m at Kole-Malekabad. From Agh-Darband, the formation thickens progressively westward, with measured thicknesses of 750 m at Qareh-Qeytan, 1263 m at Ghale-Sangi, 1430 m at Bagh-Baghoo and >850 m at Mozduran (from top to only the middle of section) (Fig. 10). Each of these sections is spaced about 5 km. To the south the formation thickens to Kole-Malekabad and then thins to 1177 m at Sefid-Sang.

5. Facies associations and depositional environments

The strata are described in terms of 12 facies of conglomerate, sandstone, mudstone, and carbonate, which were assigned facies codes commencing with G, S, M, and C, respectively. The lithofacies recognized and their interpretations are shown in Table 1. When viewed in their stratigraphic context, two facies associations are recognized. The **Basal Conglomerate Facies Association** consists largely of fluvio-marine conglomerate with maximum clast size in the boulder range. The overlying **Sandstone and Mudstone Facies Association** consists largely of interbedded packages of deep-water sandstone and mudstone (Sixsmith et al. 2004; Poursoltani et al. 2007a).

5.1. Basal Conglomerate Facies Association

Strata at the base of the Kashafrud Formation at all four sites consist of 2.5 m to 25 m of boulder to pebble conglomerate interbedded with sandstone and mudstone. The association largely comprises facies Gms and Gcs, with minor occurrences of Gc, Cd, Spb, and Ms, in order of abundance (Table 1).

5.2. Sandstone and Mudstone Facies Association

Packages of sandstone and mudstone form the bulk of the Kashafrud Formation, with an abrupt basal contact on conglomerate. The mudstones contain sparse ammonites and a few gastropods, brachiopods, and belemnites, some within concretions. The sandstones, in particular the coarser and thicker beds, contain sparse fragmental shallow-water elements that include mollusks, brachiopods, crinoids, and algae, interpreted as re-sedimented. Plant fragments are abundant in many beds. Trace fossils are of the deep-water

Taenidium, Planolites beverleyensis, Psilonichnus, Rhizocorallium jenense and Scolicia ichnofacies (Madani 1977; Poursoltani et al. 2007a; Poursoltani et al. 2007b). The sandstones are sharp based, show partial Bouma sequences, and grade up into mudstones. Thicker sandstone beds commonly occur together in packets, the base of which is erosional.

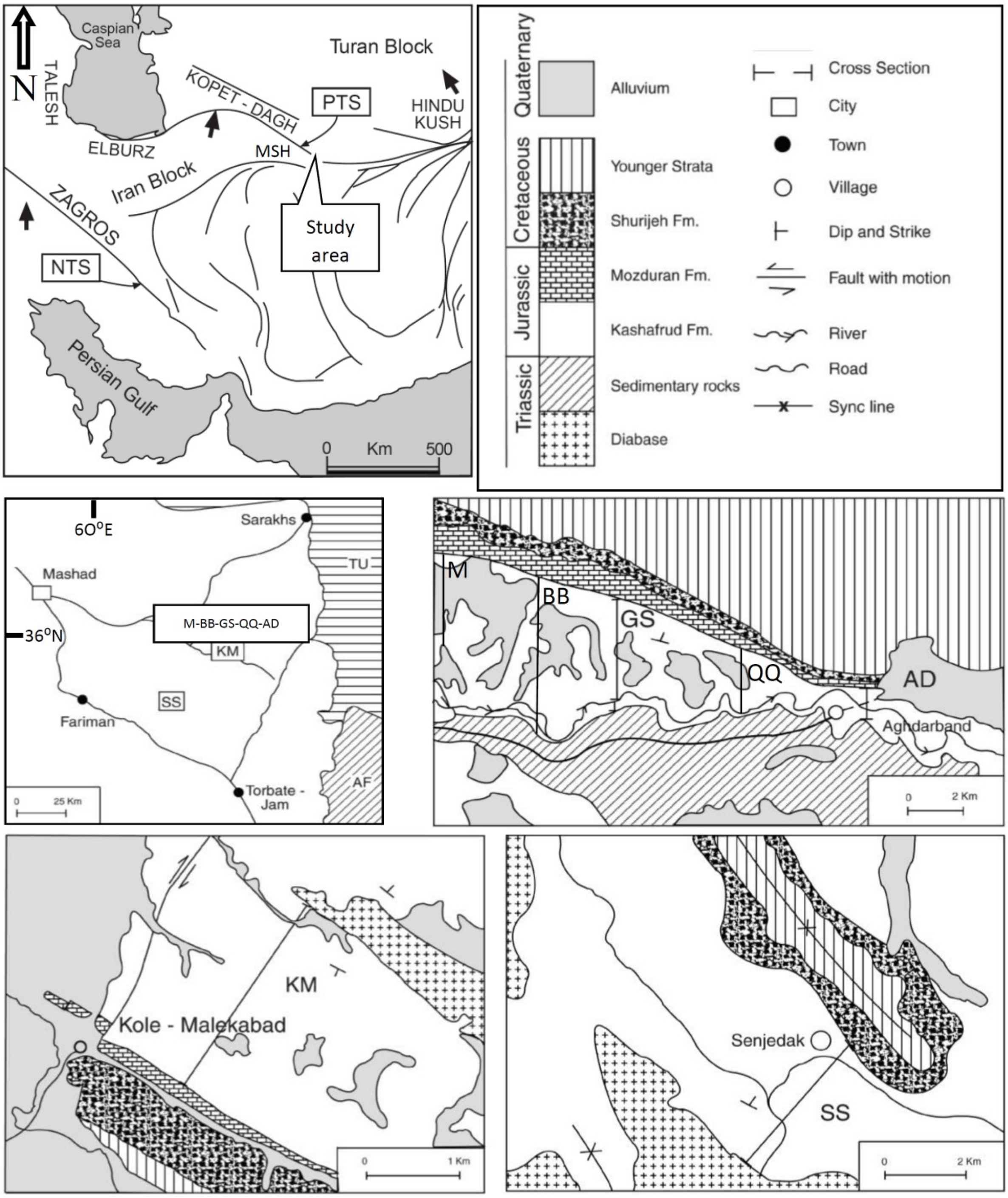

Fig. 1. A) Location map of the Kopet-Dagh Basin of northeast Iran, relative to plates and major structural lines. The arrows indicate present-day relative motions. Geological maps show the location of seven studied sections, simplified from Iran Geological Survey map sheets Sarakhs and Torbate-Jam (1:250000 scale). AF: Afghanistan, TU: Turkmenistan, AD: Agh-Darband, QQ: Qareh-Qeytan, GS: Ghale-Sangi, BB: Bagh-Baghoo, M: Mozduran, PTS: Paleothetis Suture, CI: Central Iran, HB: Helmand Block, PTS: Paleo-Tethys Suture, NTS: Neo-Tethys Suture, MSH: Mashhad. Modified from Lyberis and Manby (1999) and Poursoltani et al., (2007a).

Table 1. Summary of characteristics and interpretation of lithofacies in Kashafrud Formation (modified from Poursoltani et al., 2007a).

Facies	Sedimentary features	Depositional Conditions
G: Conglomerate		
Gms Matrix-supported conglomerate	Monomictic conglomerate in units such as AD section, up to 10 m thick. Clasts < 50 cm diameter, well-rounded to subrounded, well sorted to poorly sorted. Clasts show little preferred orientation, some imbricated, normal grading rarely present. Rests on flat-lying to concave-up erosion surface. Internal erosion surfaces in some units.	Cohesive debris flows to hyperconcentrated density flows in fluvio-marine setting.
Gcs Clast-supported conglomerate	Monomictic conglomerate in units, such as QQ , GS, BB and KM sections up to 20 m thick. Clasts < 40 cm diameter, well rounded to angular in different sections. Crude stratification, imbrication common, inverse grading. Commonly rests on concave-up erosion surface.	Stream flows and concentrated debris flows in fluvio-marine setting.
Gc Carbonate Conglomerate	Single, poorly stratified 9 m unit in basal conglomerates at SS section, and 3 m bed at AD section. Carbonate clasts 5-50 cm in diameter, matrix-supported, imbricated. Clasts from bedrock or intrabasinal origin.	Fluvial streamflow deposits with organized flow.
S: Sandstone		
Sth Thick-bedded Sandstone	Thick-bedded, medium- to very coarse-grained sandstone, with minor mudstone. Units tens of centimeters to several meters thick. Structureless, normal to inverse grading, minor cross-beds. Erosional surfaces prominent. Slumped zones. Plant and bivalve fragments, trace fossils.	Concentrated density flows to high-density turbidity flows, typically within submarine channels, near-channel sheets, and coarser lobes.
Stb Thin-bedded Sandstone	Thin-bedded, fine- to very fine-grained sandstone, mudstone interbeds. Sole structures, planar lamination, ripple cross-lamination, ripple-drift cross-lamination, and cross-beds common. Convolute lamination, load casts, and sand volcanoes. Plant fragments, trace fossils.	Turbidity flows, as distal overbank sheets. Deposits of levees, finer lobes, interlobe areas, and basin-floor sheets.
Spb Pebbly sandstone	Poorly sorted, medium- to fine-grained sandstone with scattered extrabasinal granules and pebbles. Structureless, minor cross-beds and graded beds (normal and inverse). Cross-bedded occurrences are present with the basal conglomerates of the GS section.	Concentrated or hyperconcentrated density flows, in submarine channels (Sandstone and Mudstone F.A.). Lower-regime flow in fluvio-marine channels (Basal Conglomerate F.A.).
Smc Mudclast Sandstone	Thin (2-10 cm) beds with mud clasts up to 3 cm diameter in sandy to muddy matrix. Plant fragments common. Rest on erosional surfaces.	Erosional density flows that reworked muds, in submarine channels.
Sc Calclithite	Single 1 m unit, interbedded with sandstone and mudstone at 1030 m in the KM section. Thin section shows microspar, no fossil fragments noted.	Turbidity flow of reworked carbonate.
Sd Dolomitized calclithite	Single 10 m unit in basal part of AD section. Well bedded and highly fractured, with carbonate veins. Upper parts contain more silicate grains. Framework and veins composed predominantly of sand-size dolomitized grain. No shell fragments observed.	Origin uncertain, possibly paleosol, or highly altered carbonate.
M: Mudstone		
Mm Massive Mudstone	Structureless green-grey mudstones, local lamination. Calcareous concretions, 5–45 cm in diameter, near-spherical but a few discoidal. Some dark organic-rich zones.	Suspension deposits from turbidity-flow tails and hemipelagic fallout.
Ms Silt-rich Mudstone	Rhythmic alternation of mudstone and siltstone. Siltstone in cm-scale layers, with planar lamination, ripple cross-lamination (starved formsets). Trace fossils, plant fragments.	Low-density turbidity flows and suspension settling.

Ma	Period	Stage	Formation (Lithology)
	CRETACEOUS	NEOCOMIAN	**SHURIJEH** (sandstone, conglomerate, shale, rarely evaporite)
145.6 – 152.1	JURASSIC	TITHONIAN	hiatus
152.1 – 157.1		KIMMERIDGIAN OXFORDIAN	**MOZDURAN** (limestone, dolostone, shale, sandstone, evaporite)
157.1 – 161.3		CALLOVIAN	hiatus
161.3 – 173.5		BATHONIAN to UPPER BAJOCIAN	**KASHAFRUD** (sandstone, conglomerate, shale)
173.5			hiatus
Sina Fm. (Triassic) and Igneous Rocks			

Fig. 2. Generalized Jurassic and Lower Cretaceous stratigraphy of the study area (not to scale). Approximate ages for the formations are based on biostratigraphic studies (Aghanabati 204), linked to the timescale of Gradstein et al. (2004).

6. Depositional Sequences and Sequence Boundaries

6.1. Introduction

Excellent exposure along the outcrop belt of the Kashafrud Formation and information on lateral and vertical lithofacies variations and contents facilitated the sequence stratigraphic interpretation of these strata. As a guide, we used the principal sequence stratigraphic concepts developed by researches (Van Wagoner et al. 1988; Posamentier and Vail 1988; Posamentier et al. 1988; Van Wagoner et al. 1990; Emery and Myers 1996) to recognize sequence boundaries, parasequences, stacking patterns, and maximum flooding surfaces.

6.2. Sequence boundaries in fluvial sediments

In the basal part of the conglomerate laterally equivalent to the main Kashafrud Formation, crudely bedded conglomerates (Gms, Gcs and Gc) predominate. Some of the clasts, carbonate and igneous, are rounded to subangular. The lower contact of the formation is exposed, and the clasts indicate a major unconformity with the underlying units, all of which have been exposed to erosion. This major unconformity is considered a sequence boundary, indicating deep erosion and possibly the development of channels. Some pebble to cobble-sized gravelly beds are up to 9 m thick (e.g. Fig. 4A-B).

Other coarse-grained facies consist predominantly of massive granule to pebble-sized conglomerate and trough cross-bedded, a fluvial facies, feldspathic litharenite to litharenite and pebbly sandstone (Spb) (e.g. Fig. 5B). The palaeocurrent data show a general northwesterly trend (Poursoltani et al. 2007a).

Interpretation

The prominent and widespread erosion surfaces that are overlain by coarse grained fluvial channel deposits, at the base of formation, are interpreted as sequence boundaries because (1) these erosion surfaces are overlain by fluvial deposits (channel deposits) that mark a significant seaward facies shift, (2) the depth of incision is significant, implying a fall of relative sea-level to its lowest position.

6.3. Sequence stratigraphic correlation

A maximum of five depositional sequences (parasequences) have been recognized in the thickest section at Kole- Malekabad (Fig. 8). Assuming the basal depositional sequence in each measured section is correlative, the depositional sequences can be correlated thoughout the basin (Fig. 10). Passing northeastward, the upper sequences are cut-out by the base-Oxfordian unconformity.

7. System tracts and sea level control

7.1 Sea level changes

Based on the recognition of facies stacking patterns with parasequences, it is possible to evaluate the effects of long- to medium-term changes in relative sea-level, and connections with tectonism and sediment supply (Hampson and Storms 2003). Each of the stratigraphic sequences would be expected to consist of:

(1) lowstand deposits, just above the major erosion surface of the sequence boundary
(2) transgressive deposits
(3) maximum flooding surface
(4) highstand or falling stage deposits

Such features are readily interpreted in fluvial to deltaic sediments, but much more difficult ro recognise

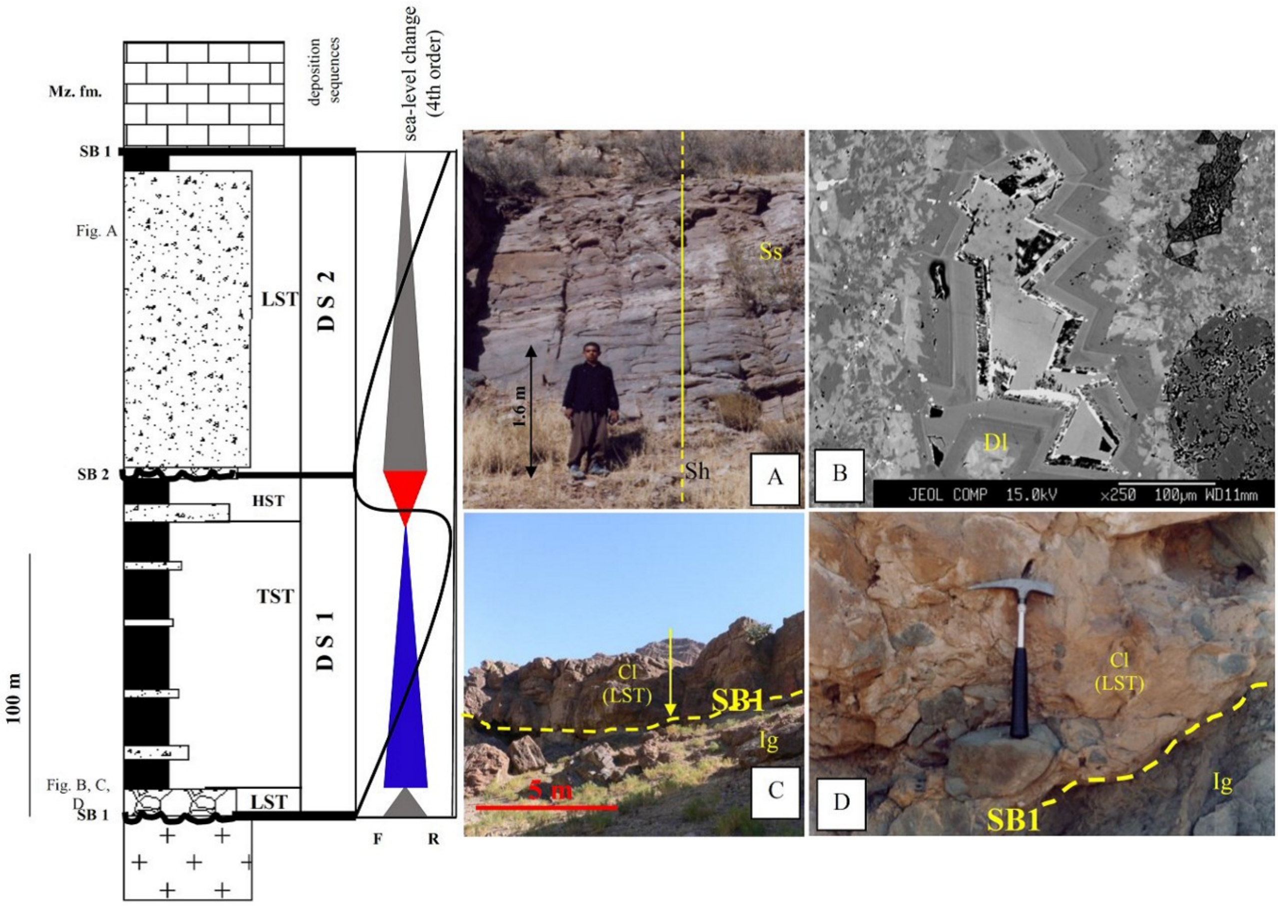

Fig. 3. Detail of sequence stratigraphic interpretation of the Upper Bajocian-Lower Bathonian at the Agh-Darband section (for location see Fig. 1.). A) thick red sandstone at the upper part of section as LST; B) dolomitic limestone at the lower part of section as LST; C) basal contact of Kashafrud Formation with older rocks (igneous) as LST. Erosional surface as 1st SB is shown; D) paraconglomerate monomictite, with carbonate cement and igneous clasts are shown; (SB: sequence boundary; DS: depositional sequence; Ss: sandstone; S: shale; Dl: dolomite; Cl: conglomerate; Ig: igneous; F: falling; R: rising).

convincingly in turbidite successions. At lowstands, sediment delivery is direct to the basin slope and characterized by abundant sandy sediment supply. Under conditions of rising sea level, sediment may be trapped on the shelf and in estuaries, resulting in predominantly mud deposition in the basin. The maximum flooding surface may be marked by slow sedimentation rates and the accumulation of pelagic fossils and organic carbon. Once progradation of deltas across narrow shelves resumes, there is an increase in sand supply to the basin.

7.2. Lowstand deposits

The fluvial units are in some sequences up to 20 m thick. Fine-grained overbank deposits adjacent to the fluvial channel are documented in major places, and are characterized by erosional surfaces and thick-bedded and locally thin-bedded, ripple-cross - laminated, very fine to mostly pebbly sandstones, and conglomerate (Figs. 3-9).

Interpretation

The successions of coarse-grained fluvial deposits that shift abruptly seaward across older deltaic-sea floor deposits of previous sequences are interpreted as lowstand deposits. The upwards transition from fluvial to deeper deposits indicates deposition during relative sea-level rise. In those sequences that show vertically stacked fluvial channel deposits (Figs. 3A-C-D, 4A-B, 5B, 6B, 8E, 9C-D) separated by mud-prone flooding intervals, the channel fill is represented as early lowstand fill, whereas the upper channel deposits belong to late lowstand. This kind of intra-lowstand flooding surface has been described also from contemporaneous shallow to deep-marine deposits (Plink-Björklund 2005; Plink-Björklund and Steel 2005). The rising sea-level would have drowned incised river mouth or distributary channels, and caused temporary sand storage in the fluvial system, until the fluvial systems aggraded, and deltaic systems prograded back to the shelf edge again to form the late lowstand deltas (Plink-Björklund et al. 2001; Plink-Björklund and Steel 2005).

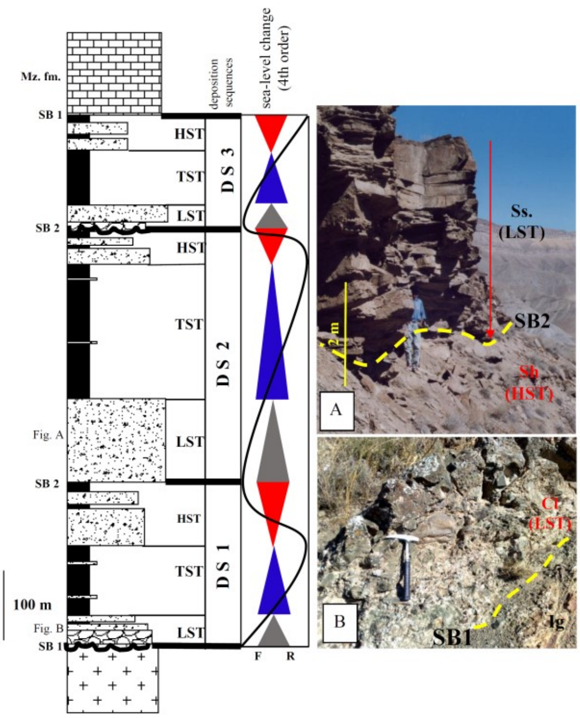

Fig. 4. Detail of sequence stratigraphic interpretation of the Upper Bajocian-Lower Bathonian at the Qareh-Qaytan section (for location see Fig. 1). A) thick-bedded sandstone as LST, resting on thick bed of shale. The erosional surface (dashed line) has been recognized as SB2; B) basal conglomerate and SB1 at 1st depositional sequence.

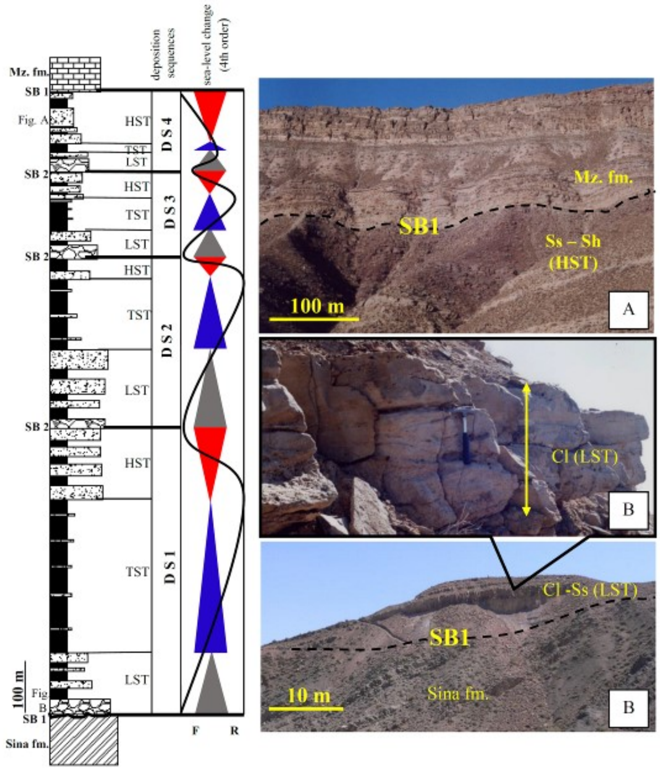

Fig. 5. Detail of sequence stratigraphic interpretation of the Upper Bajocian-Lower Bathonian at the Ghale-Sangi section (for location see Fig. 1). A) contact of Kashafrud Formation and Mozduran Formation (Mz. fm.). Red sandstones and shale beds are assigned to HST; B) contact of Kashafrud Formation and Sina Formation and 1st sequence boundary (SB1). Basal conglomerate and sandstone is assigned to LST.

7.3. Transgressive deposits

The fluvial channel deposits are generally overlain by deltaic deposits (Figs. 8C, 9B). The deltaic deposits rest on highly erosional basal surfaces that in some cases cut through the whole underlying fluvial deposits (LST), and merge with the sequences-bounding erosion surface. The transgressive deposits volumetrically dominate the depositional sequences. In contrast to the lower, fluvial depositional segments, the middle transgressive segments are mud-prone, and the only thick and prominent sands are those that occur as channel bodies. The channels are also sandy, but the sands are rather thin (9 m thick) and discontinuous.

The majority of the mudstones were deposited on migrational distal fans. Depositional units of sand to mud have a coarsening/fining upward in the transgressive segment, as gradually higher energy of the fluvial systems cover the lower energy areas.

Interpretation

The landward-stepping deltaic successions that accumulated above the lowstand deposits are interpreted as transgressive deposits. A relative sea-level rise is indicated by a landward shift in all depositional environments, a landward onlap.

7.4. Maximum flooding surface

The maximum flooding surface (mfs) is marked by layers of ammonite and ostreid fossils (Coe 2005), such as at Kole-Malekabad and Sefid-Sang sections, in the first depositional sequence. Locally, high amounts of organic matter in some layers may indicate maximum flooding levels associated with the major depositional sequences. But generally, maximum flooding slurfaces have not been indentified clearly, or we could not recognize them.

7.5. High-stand deposits

The high-stand deposits where present (Figs. 5A, 6A, 8A-B-D, 9A-C), comprise sedimentary facies similar to those in the underlying transgressive deposits. The high-stand segments differ from the transgressive segments by, (1) a seaward-shift of submarine fan (turbiditic) facies, and (2) a higher proportion of sandstone deposits.

Interpretation

The seaward-stepping turbiditic successions indicate decreasing rates of sea-level rise, and are assigned to the high-stand systems tract.

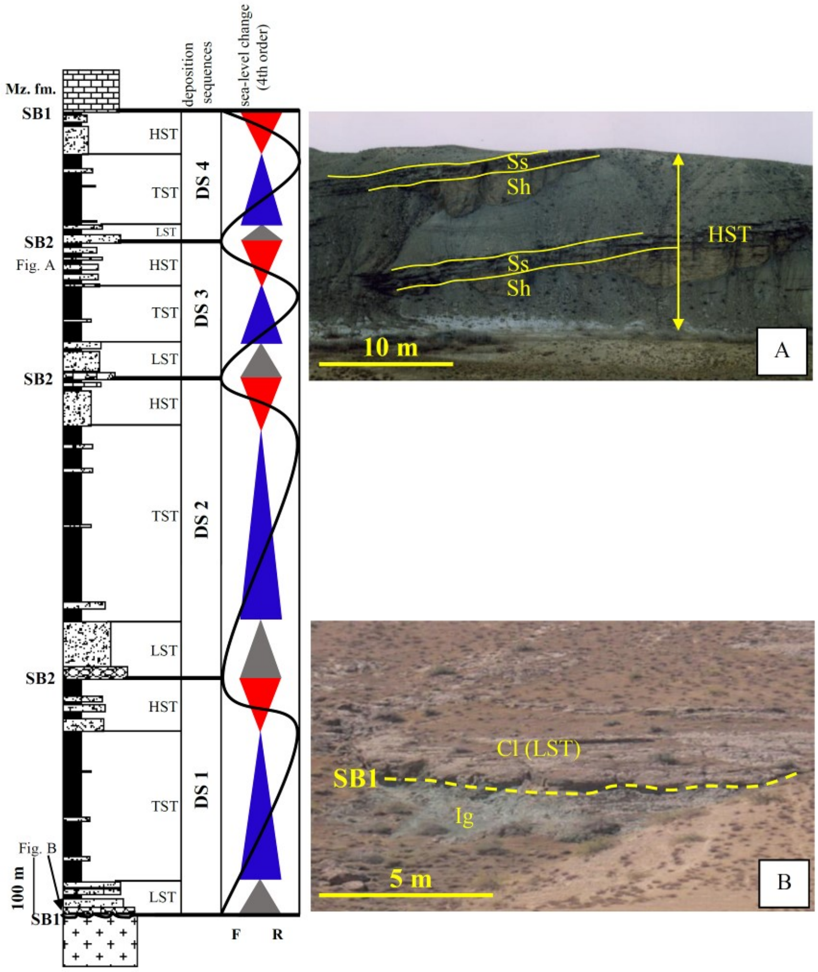

Fig. 6. Detail of sequence stratigraphic interpretation of the Upper Bajocian-Lower Bathonian at Bagh-Baghoo section (for location see Fig. 1). A) a part of HST from 3rd depositional sequence; B) sequence boundary (SB1) (dashed line), and contact of Kashafrud Formation and older rocks (igneous). Basal conglomerate is assigned to LST.

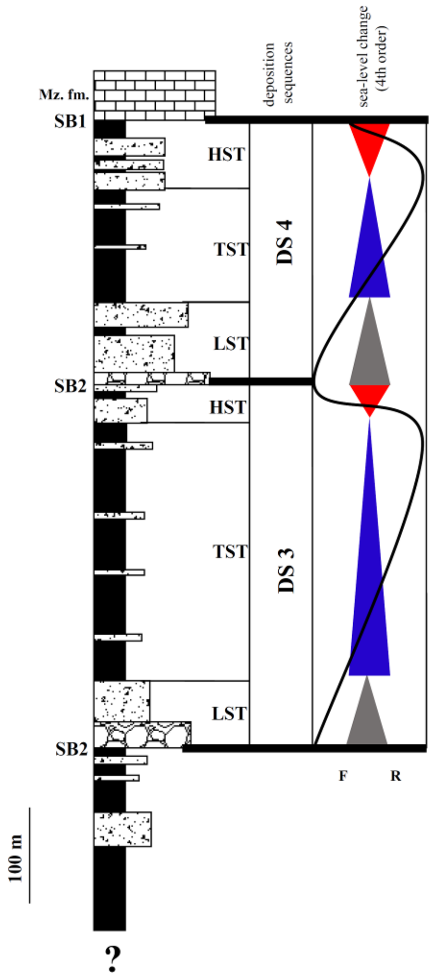

Fig. 7. Detail of sequence stratigraphic interpretation of the Upper Bajocian-Lower Bathonian at Mozduran section (for location see Fig. 1). Lower part of section is covered.

8. Controls on stratigraphic architecture

As discussed by Poursoltani et al. (2007a), many architectural aspects of deep-sea systems have been related to sea-level change (Sixsmith et al. 2004; Plink-Björklund 2005). Within some smaller basins, changes in sea-level may have important consequences, although they also result in complex changes in sediment-transport pathways and in the mechanisms of turbidite initiation (Piper and Normark 2001). However, other authors have inferred that deep-water events mainly represent autogenic effects such as channel and lobe switching. Chen and Hiscott (1999a) and Chen and Hiscott (1999b), in a study of the clustering of deep-water attributes in satratigraphic successions, suggested that tectonic effects and complex triggering processes commonly mask orderly sea-level cycles.

For the Kashafrud Formation, the lack of evidence for coeval facies tracts in the study area precludes correlation between shelf, slope and basin systems. However, the basin-margin setting with bedrock valleys and the probable presence of active faults implies that tectonics and sediment supply were important factors in architectural development. Some episodes of channel-base erosion and gravel transport may reflect sea level lowering. Some organic-rich mudstones and layers of concentrated ammonites may reflect sea-level rise and regional sediment starvation (Sixsmith et al. 2004); however, the extent of these units is not known, and they may also reflect the vagaries of local sediment supply, anoxic conditions, and mortality events. No Jurassic ice caps are known, and glacioeustatic effects were probably minimal at this time. Consequently, we provisionally infer that Kashafrud architecture largely reflects a combination of autogenic and tectonic controls.

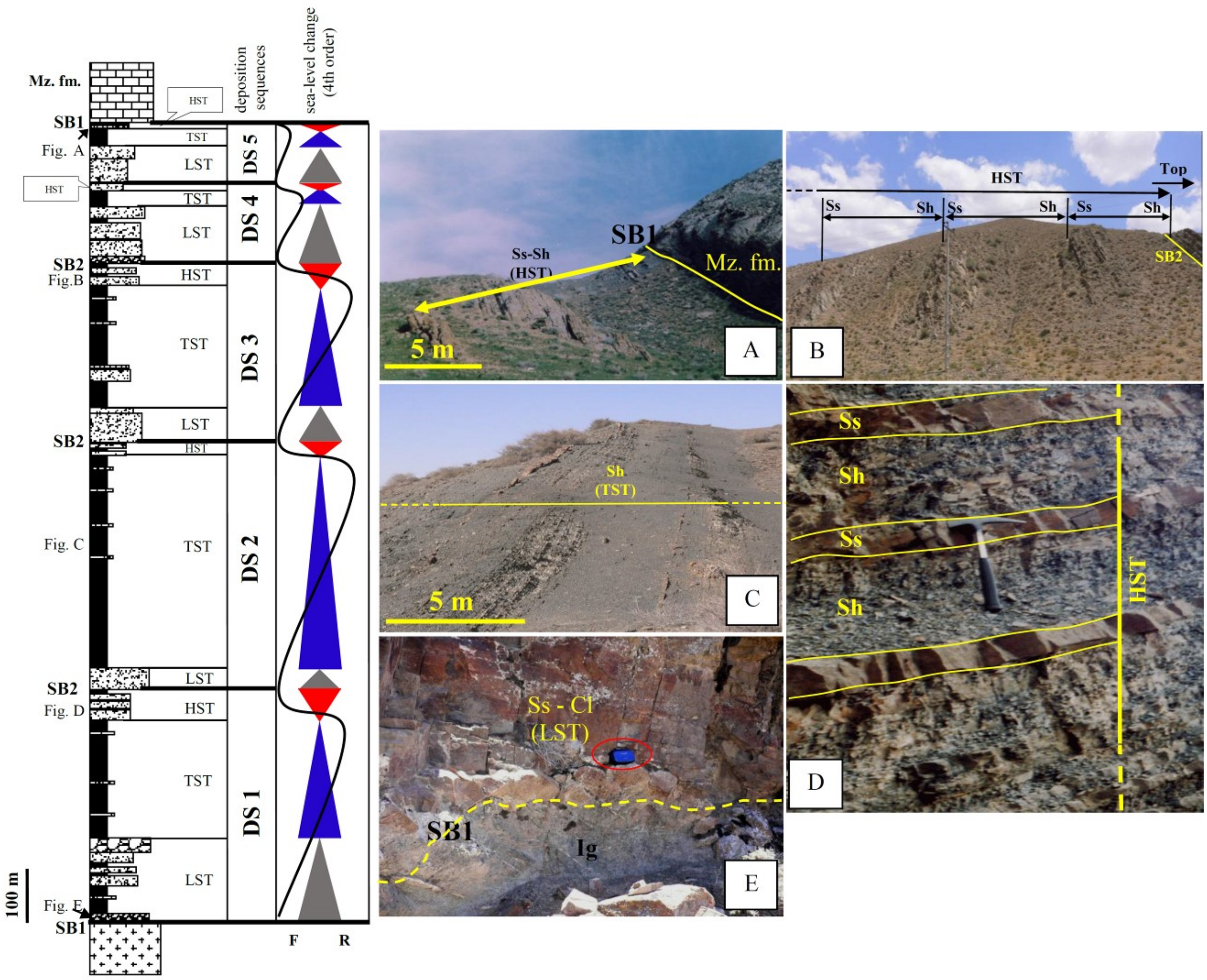

Fig. 8. Detail of sequence stratigraphic interpretation of the Upper Bajocian-Lower Bathonian at Kole-Malekabad section (for location see Fig. 1). A) Contact of Kashafrud Formation with Mozduran Formation (Mz. fm.); B and D) alternation of sandstone and shale shown as upper part of HST (1st and 3rd depositional sequence); C) thick-bedded shale shown as TST (2nd depositional sequence); E) 1st sequence boundary (SB1), and contact of Kashafrud Formation with older rocks (igneous) (camera cover is 12 cm, circled).

9. Depositional sequences

9.1 Depositional sequence 1 (DS1)

The DS1 depositional sequence is present in lower part of the Kashafrud Formation in all sections (Fig. 10). The basal boundary is marked by an erosional surface, which differentiates the Kashafrud Formation from the older rocks (SB1). The DS1 rests unconformably on older rocks. The thickness of this depositional sequence is variable, with a minimum at Agh-Darband section (146m) and maximum at Ghale-Sangi section (585m). In Kashafrud Formation, rising sea level caused the filling of channel bodies. The pebbly sandstone (Spb) and conglomerate (Gms, Gcs) layers are interpreted as lowstand deposits, covered by transgressive deposits. The existence of thick-bedded shale (Ms) and isolated channel bodies are interpreted as transgressive system tracts (Coe 2005; Catuneanu 2003; Catuneanu 2006). In Kole-Malekabad and Sefid-Sang, the maximum flooding surface (mfs) is marked by ammonite and ostreid fossils.

9.2. Depositional sequence 2 (DS2)

Sea level continued to rise, causing the DS2 depositional sequence to be deposited. The DS2 was observed at all sections that rest on DS1, but its thickness is variable, with a minimum at Agh-Darband section (134m) and maximum at Bagh-Baghoo section (545m). The basal boundary is marked by erosional surfaces in all sections. The existence of conglomerate (Gms and Gc), pebbly sandstone (Spb), and thick-bedded sandstone indicate a lowstand system tract. In some sections incised valleys have been identified.

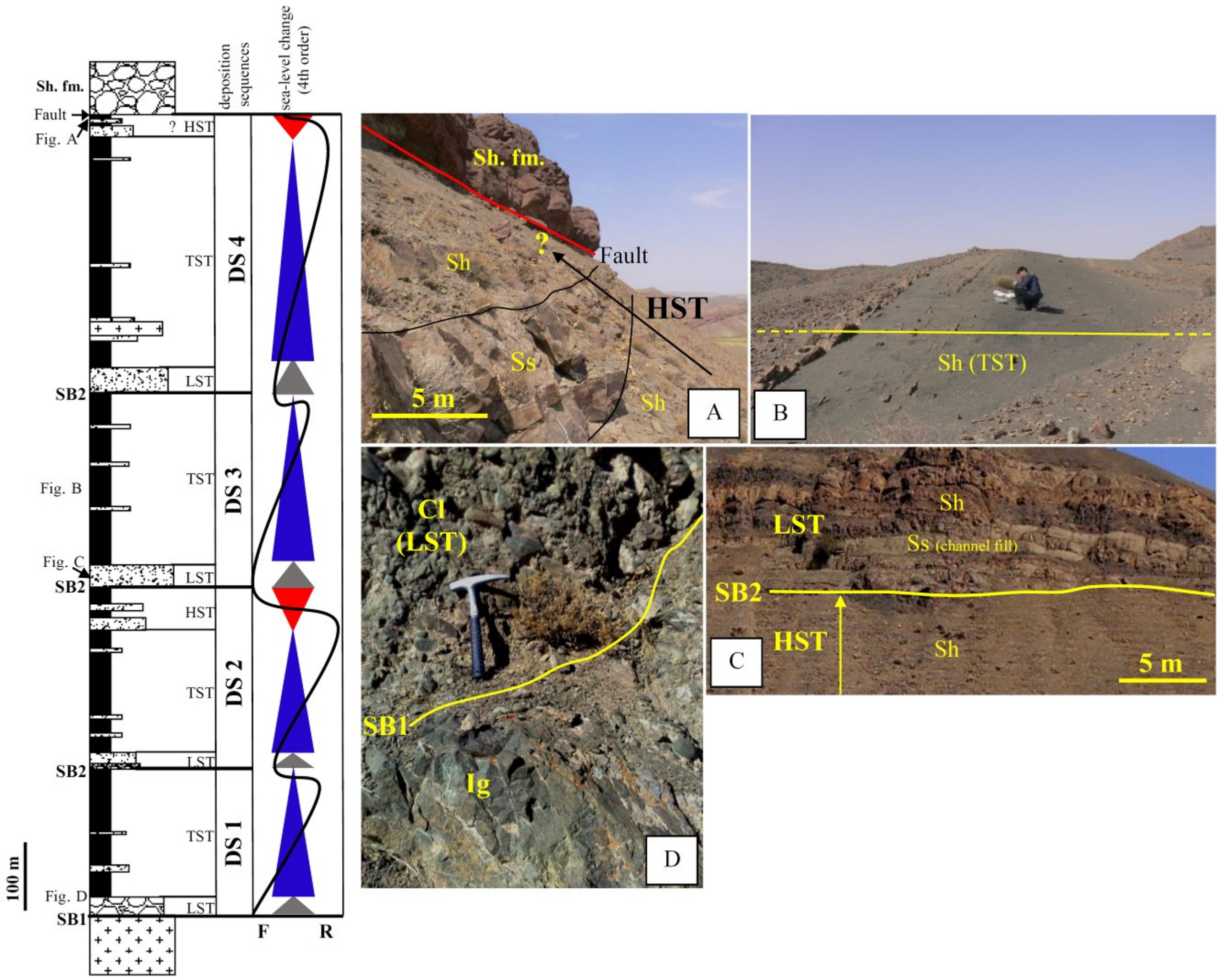

Fig. 9. Detail of sequence stratigraphic interpretation of the Upper Bajocian-Lower Bathonian at Sefid-Sang section (for location see Fig. 1). A) Contact of Kashafrud Formation with Shurijeh Formation (Sh. fm.) due to faulting (with line), and upper part of 4th depositional sequence (HST?); B) thick-bedded shale shown as TST, 3rd depositional sequence; C) sequence boundary (SB2), and channel bodies shown as LST in 3rd depositional sequence; D) contact of Kashafrud Formation and older rocks (igneous), shown as 1st sequence boundary (SB1). Basal conglomerate is assigned lower part of LST.

Thus, thick-bedded shales (Ms) interbedded with thin-bedded sandstones are interpreted as the transgressive systems tract, and thin-bedded sandstones (Stb) with shale beds are attributed to the high stand systems tract. In this depositional sequence a maximum flooding surface has not been identified. At Agh-Darband section, this depositonal sequence is the last DS, and the Mozduran Formation, a carbonate unit, rests conformably on the Kashafrud Formation (Fig. 3).

9.3. Depositional sequence 3 (DS3)

DS3 was observed at all sections, except Agh-Darband section. The minimum thickness of this depositional sequence is 193 m at Ghale-Sangi, and maximum thickness is 420 m at Sefid-Sang section. The basal boundary is marked by erosional surfaces and channel fills. At all sections, this depositional sequence rests on DS2. Existence of thick-bedded pebbly sandstone (Spb) and conglomerate at major sections indicates a lowstand sytems tract. Thus, thick- bedded shales are interpreted as part of the transgressive systems tract, and thin-bedded sandstones (Stb) with shale beds as part of the highstand systems tract, except at Sefid-Sang section where the HST did not form. In all sections, a maximum flooding surface has not been identified. Due to tectonic effects, this depositional sequence is the last DS at Qareh-Qeytan section, where the Mozduran Formation rests conformably on the Kashafrud Formation (Fig. 4).

9.4. Depositional sequence 4 (DS4)

Continuing sea level rise caused the fourth depositional sequence to be deposited, resting on DS3. DS4 was observed at all sections except at Agh-Darband and Qareh-Qeytan sections. It's thickness is variable, with a minimum at Ghale-Sangi (155m) and maximum at Sefid-Sang section (380m). The basal boundary is marked by incised valleys and erosional surfaces. In all sections, DS4 is the last DS, thus, in Kole-Malekabad section, continues of precipitation caused the DS5 formed.

The identified facies indicate that in all sections DS4 consists of LST, TST and HST systems tracts, but the thickness of HST at Sefid-Sang section in not truly. In this section, the faulting caused the Surijeh Formation tp rest on Kashafrud Formation, but probably some part of the Kashafrud Formation has been lost (Fig. 9A).

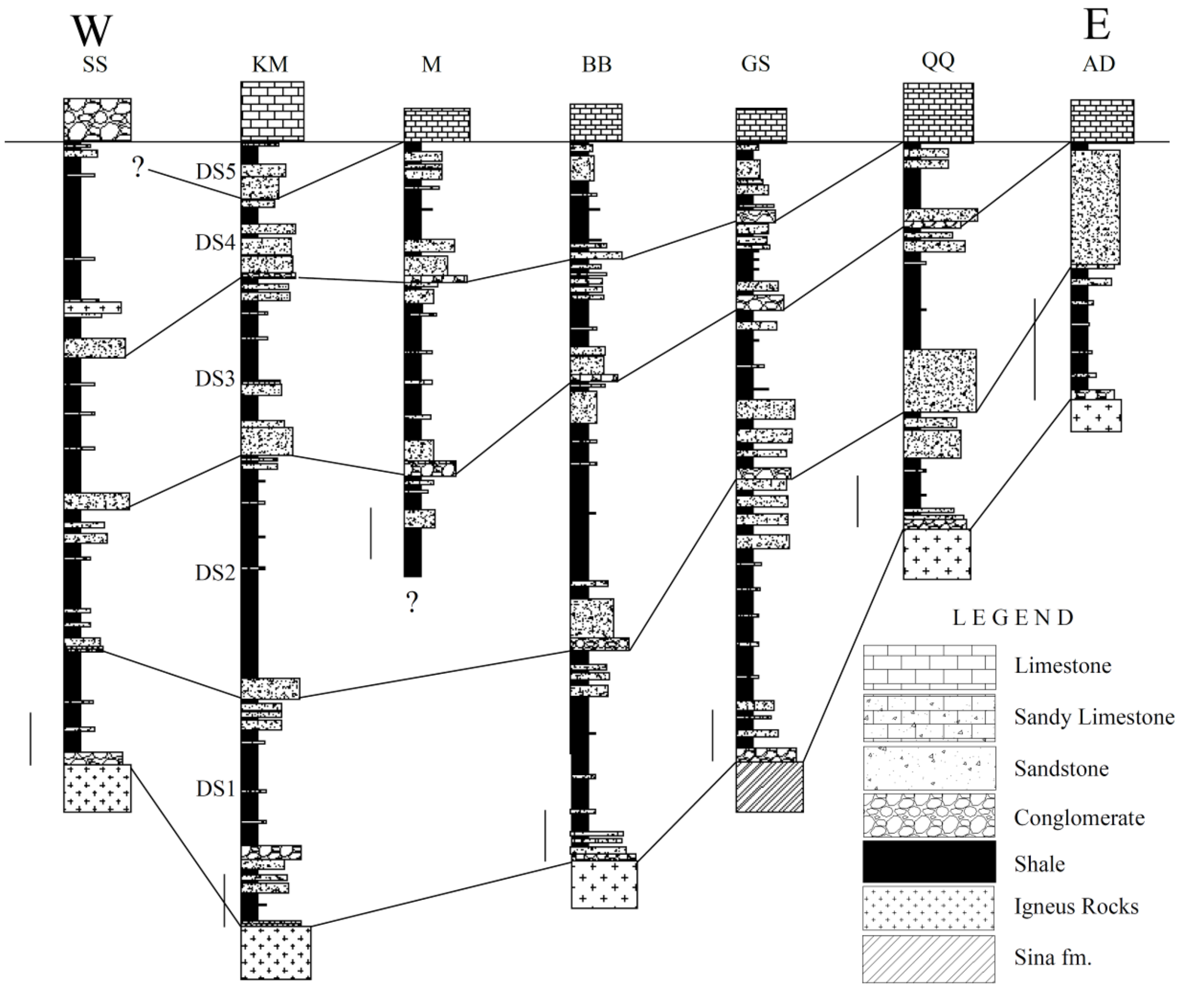

Fig. 10. Correlation of seven measured sections, based on depositional sequences and similar facies. Vertical line is 100 m; horizontal distance is not to scale. For location see figure 1. (SS: Sefid-Sang; KM: Kole-Malekabad; M: Mozduran; BB: Bagh-Baghoo; GS: Ghale-Sangi; QQ: Qareh-Qeytan; AD: Agh-Darband; DS: Depositional Sequence).

9.5. Depositional sequence 5 (DS5)

Continuing uplift at major areas caused DS5 to form only at Kole-Malekabad section. The thickness of this DS is 145 m. The basal boundary is marked by erosional surfaces. At this section, DS5 rests on DS4.

Existence of thick-bedded sandstones and pebbly sandstones (Spb), and channel bodies, indicates a lowstand sytems tract. Based on facies identification, TST and HST system tracts are observed. Thus, thick-bedded shales are interpreted as the transgressive system tract, and thin-bedded sandstones (Stb) with shale beds as the highstand systems tract. In this section Mozduran Formation rests on Kashafrud Formation conformably (Fig 8A).

10. Paleogeographic interpretation

Paleogeographic reconstructions of Upper Bajocian - Lower Bathonian time (deposition of Kashafrud

Formation) are presented here as a series of block diagrams (Fig. 11). At first, the study areas were sites of erosion, marked by an angular conformity in Ghale-Sangi section, where the Kashafrud Formation rests on Sina Formation, Triassic in age, and nonconformity in other sections. The first lowstand marked by an erosion surface (SB1) produced space for the deposition of coarse- grained sediments (conglomerate and gravelly sandstones) in Qareh-Qeytan, Ghale-Sangi, Bagh-

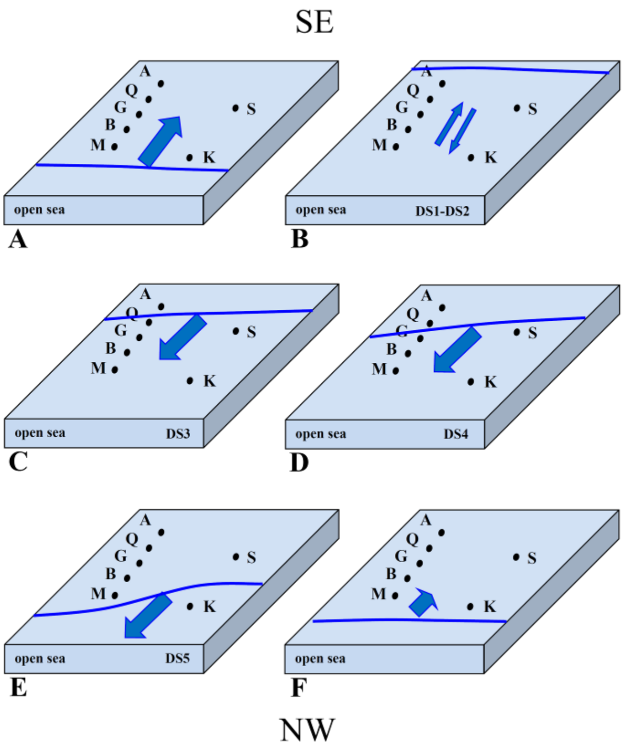

Fig. 11. Schematic cartoon showing the six main phases of sedimentation in Middle Jurassic (Upper Bajocian-Lower Bathonian), Kopet-Dagh Basin, NE Iran. For more information see the text. (Big arrows show the main transgressive events that caused the formation of SB1, whereas small arrows show minor sea level changes that caused formation of SB2) (A: Agh-Darband; Q: Qareh-Qaytan; G: Ghale-Sangi; B: Bagh-Baghoo; M: Mozduran; K: Kole-Malekabad; S: Sefid-Sang).

Baghoo, Kole-Malekabad and Sefid-Sang sections, and carbonate sediments in Agh-Darband section (Fig. 3B-C-D), with the channel-body facies developed. This was followed by “high frequency” sea-level fluctuations during the transgressive systems tract. The transgressive and regressive stages are described as follow:

1st: At the first stage, all sections were erosional (SB1), and transgressive deposits started to form the first depositional sequence (Fig. 11a).

2nd: (transgression, mfs, DS1, DS2), during this time, all sections were a site of sedimentation, and two events of transgression and regression occurred but not for a long time, forming SB1. During this time DS1 and DS2 were formed. At this stage, only in Sefid-Sang and Kole-Malekabad have maximum flooding surfaces (mfs) been identified (existence of ammonites and ostreids) (Fig. 11b).

3rd: At the third stage, it is assumed that during this time, due to tectonic uplift, regression started, and as a result section Agh-Darband paleohigh was exposed to erosion, but other sections were sites of sedimentation (3rd depositional sequence, DS3). At Agh-Darband SB1 formed (red sandstones at top of section), and the Mozduran Formation rests on Kashafrud strata (Fig. 11c).

4th: At this stage, continued uplift and regression took place, Qareh-Qeytan section was exposed to erosion (SB1), and other sections were sites of marine sedimentation (4th depositional sequence, DS4) (Fig. 8d).

5th: At this stage, due to tectonic uplift, regression continued, SB1 formed and only section Kole-Malekabad was a site of sedimentation (5th depositional sequence, DS5). It is not clear about events in the Sefid-Sang section (Fig. 11e).

6th: During this stage, all sections were erosionaall, SB1 formed and transgressive deposits are associated with the Mozduran Formation at a carbonate ramp (Lasemi 1995; Kavoosi et al. 2009) (Fig. 11f).

11. Conclusions

The sedimentary rocks of the studied area attest to an extensional development for a fluvio-deltaic to turbiditic cyclic succession of about 7 Ma duration. The parasequences identified here are probably related mostly to high-frequency cycles of relative sea-level change due to tectonic movements. For the Kashafrud Formation, the lack of evidence for coeval facies tracts in the study area precludes correlation between shelf, slope and basin systems. However, the basin-margin setting with bedrock valleys and the probable presence of active faults implies that tectonics and sediment supply were important factors in architectural development. Consequently, we provisionally infer that Kashafrud Formation architecture largely reflects a combination of autogenic and tectonic controls. Tectonism, compaction and rate of deposition were the main factors that controlled the vertical facies transitions in these parasequences. As more data on cyclicity within Middle Jurassic rocks is accumulated, it may be possible to differentiate eustatic sea-level cycles from local tectonic cycles.

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