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Ichnotaxonomic analysis and depositional controls on the carbonate ramp ichnological characteristics of the Deh-Sufiyan Formation (Middle Cambrian), Central Alborz, Iran

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Abstract

The trace fossil assemblages from the Unit 2 of Deh-Sufiyan Formation are described for the first time from The Central Alborz Range of northern Iran, improving the record of the assemblages in the Cambrian of the Middle East. Twenty-one ichnogenera have been identified in the Deh-Sufiyan Formation, namely Arenicolites, Bergaueria, Chondrites, Circulichnus, Cruziana, Diplichnites, Didymaulichnus, Diplocraterion, Halopoa, Helminthopsis, Gordia, Gyrophyllites, Lockeia, Monomorphichnus, Palaeophycus, Phycosiphon, Planolites, Rosselia, Rusophycus, Skolithos, and Treptichnus. Characteristics of the facies, lateral and vertical relations between these facies, associational types of the facies and the depositional profile of the shelf transect examined show deposition on a wave-dominated carbonate ramp. Integration of ichnologic data with sedimentologic information supports a firm interpretation of the depositional systems and their evolution. Ethological grouping of the trace fossils resulted from the physico-chemical depositional constraints which defines the proximal-distal ichnofacies gradient pattern of the wave-dominated successions of the Deh-Sufiyan ramp. Considering the obvious deepening of the shallow marine depositional systems of wave-dominated parts of the carbonate ramp, the succession of archetypal ichnofacies can display a bathymetric trend from deeper to shallower parts, and from lower-to-higher hydrodynamic conditions, from the bottom to the top of the Unit 2 of the Deh-Sufiyan Formation. The identification and interpretation of the archetypal ichnofacies are employed to further refine the sedimentary interpretations of parameters such as wave energy, substrate properties, nature of available food supply, salinity, dissolved oxygen content, and variability in sedimentation rates.

Keywords: *Deh-Sufiyan Formation, Middle Cambrian, ichnotaxonomic analysis, ichnological attributes, carbonate ramp.*

1. Introduction

The integration of ichnologic data with sedimentological analysis permits the discrimination among lithologically similar facies. In detail, the distribution of trace fossils in wave-dominated settings is complex and is greatly controlled by substrate conditions in terms of the degree of consistency, and grain size distribution. For instance, ichnological data have been used to help distinguish between proximal and distal facies of shoreface-offshore successions on broad spatial scales (Pemberton et al. 1992; Pemberton and MacEachern 1997; Bann and Fielding 2004; MacEachern et al. 2007a; Bayet-Goll et al. 2015a, b). An integrated approach combining various potential environmental indicators, taken from ichnology and sedimentology, has considerably enhanced the palaeoenvironmental interpretations of this study, which regards the Middle Cambrian Deh-Sufiyan Formation, Iran (Fig. 1). This paper is aimed at discussing the distribution and diversity of trace fossils and sedimentologic significance of the Unit 2 of the Deh-Sufiyan Formation's ichnofossils.

2.Geological Background

The Alborz and adjacent Central Iranian blocks are regarded to be parts of a fragment of the early Paleozoic Gondwanan passive margin, rifted away from Gondwana during the Ordovician to Silurian periods then collided with Eurasia during the Triassic (Berberian and King. 1981; Stöcklin 1974). According to Berberian and King (1981) following the Late Precambrian (Katangan) orogeny and the consolidation of the basement, the Precambrian craton of Iran, Pakistan, central Afghanistan, southeastern Turkey, and Arabia became a relatively stable continental platform with epicontinental shelf deposits (mainly clastics), displaying no evidence of major magmatism or folding events. The stratigraphic succession of the Central Alborz (Alavi 1991) spans the entire Phanerozoic and is roughly 11 to 13 km thick. The Precambrian and Cambrian succession (3000-3500m thick) is represented by coastal sandstones and dolostones, with continental

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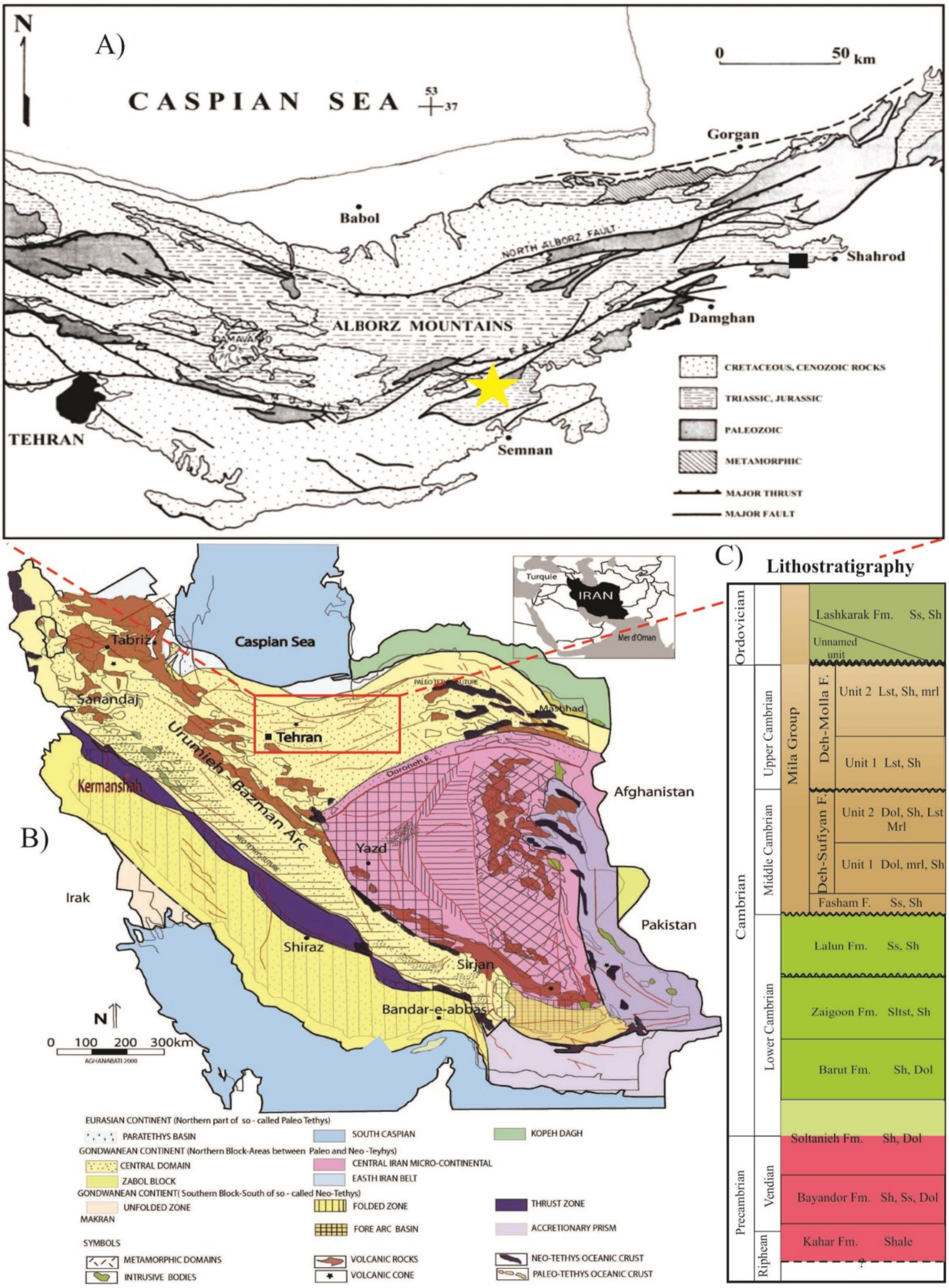

Fig 1-A) Simplified geological map of the study area, the eastern part of the Alborz Mountain Range (modified after Aghanabati 2004). B) Geological map of Iran with its structural provinces (modified from Aghanabati 2004). C) Simplified lithostratigraphy of the Alborz Mountains (modified after Geyer et al. 2014). Sh, shale; Ss, sandstone; Dolo, dolomite; Sltst, siltstone; Mrl, marlstone; Lst, limestone.

deposits in the Early Cambrian. The Cambrian-Ordovician strata of the Alborz Mountains in northern Iran consist of a succession of alternating carbonate and siliciclastic units (Hamdi 1995) showing eustatic sea level changes. The Palaeozoic succession in the Central Alborz has been split in ascending order into the Zaigun, Lalun, Mila, and Lashkerak formations (Stöcklin 1974). According to studies of Peng at al. (199), Geyer et al. (2014) and Bayet-Goll et al. (2014), the Mila Formation, as opposed to what traditionally applied, shows several inconsistencies in definition and physical properties, which require a total lithostratigraphic revision. The published lithostratigraphic schemes are based on insufficient biostratigraphic and lithological information. As a result, the term "Mila Formation" cannot be applied to this large lithostratigraphic unit according to the international stratigraphic rules (Peng at al. 1999). On the other hand, a new lithostratigraphic scheme for the Cambrian–Ordovician strata of the Alborz Mountains by Geyer et al. (2014) suggests the term "Mila Group" for the lithostratigraphic unit that includes the Fasham Formation (new), the Deh-Sufiyan Formation (new), the Deh-Molla Formation (new) and the Lashkerak Formation (Fig. 2).

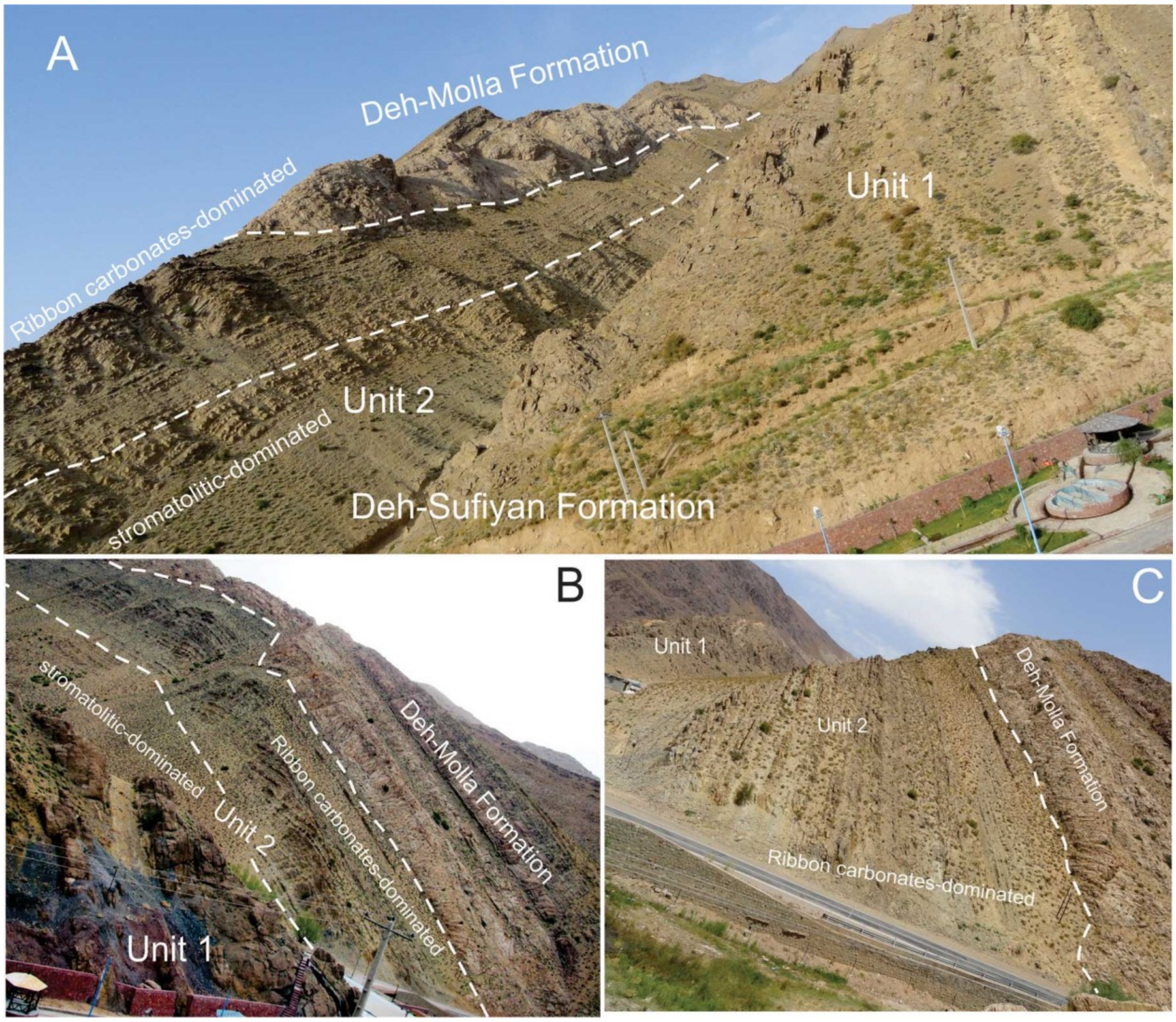

Fig 2. Field photographs of units 1 and 2 of the Deh-Sufiyan Formation A, B) Overview of units 1 and 2 of the Deh-Sufiyan Formation and the lower Deh-Molla Formation in the Shahmirzad section (N 35° 47' 38", E 53° 18' 38"). C) Panoramic view of Ribbon units of the Deh-Sufiyan Formation and the lower Deh-Molla Formation.

Two units are identified in the Deh-Sufiyan Formation (Geyer et al. 2014): Unit 1, extensively distributed, mainly carbonate succession, about 200 m thick in northern Iran. It consists of stromatolitic and marly dolostone, oncoidal dolostone, marlstone, shale, silty shale and minor thin-bedded limestone devoid of invertebrate fossils. The unit 1 ends in fine- to coarse-grained dolomites interbedded with shale and marlstone. This member transitionally passes into the unit 2 above (Geyer et al. 2014). Unit 2, is approximately 200 m thick and is divided into two distinct types. The lower part includes green shales and marlstone, stromatolitic and marly dolostone, thrombolite, skeletal limestone with dolomite interlayers, thin-bedded limestone and marlstone/dolostone (ribbon carbonate) with synaeresis cracks, evaporite pseudomorphs, ichnofossils, abundant trilobites and other invertebrate fauna (Geyer et al. 2014). The upper part comprises mainly a ribbon carbonates succession. The ribbon carbonate with a millimeter-to centimeter-scale and layers of carbonate conglomerate is a common and striking feature in the unit 2 of the Deh-Sufiyan Formation. The unit 2's lower contact with the underlying unit 1 is transitional; its upper boundary with siltstone and sandstones of the Deh-Molla Formation is inconsistent (Geyer et al. 2014). Trace fossils are a common and striking feature in the Unit 2 of the Deh-Sufiyan Formation. This paper limits its discussion to ichnotaxonomic analysis and the study of depositional controls on the ichnological attributes of the ribbon carbonates of the Unit 2 of the Deh-Sufiyan Formation. Other units are described in Bayet-Goll et al. (2014, 2015a) and are not discussed in this paper. The sedimentary rocks of the Unit 2 were studied and measured in a section situated approximately 3 km north from Shahmirzad City (coordinates N 35° 47'26.3'', E 53°18'53.6'') (Fig. 2). The principal access road to the study area is the road from Tehran to Shahrud.

3. Methods

The Deh-Sufiyan Formation was studied and measured in one section, where it is thoroughly accessible and continuously exposed (Fig. 3). Physical sedimentological attributes (texture, composition, mechanical structures, contacts, etc.) as well as vertical trends and stacking patterns, were all combined to define and interpret facies and facies associations. Ichnological attributes involved the recognition and identification of the trace fossils present, abundance and distribution of individual ichnotaxa, degree of bioturbation (Taylor and Goldring 1993), assessment of ichnodiversity, identification of trophic types and ethologic groups (Bromley 1996), and relationships among trace fossils, physical sedimentary structures, and bedding types (Monaco and Caracuel 2007), and ichnofacies recognition and subdivision (Buatois and Mángano 2011). This information provided a basis for the interpretation of sedimentary processes (facies) and depositional systems (facies associations). Seilacher (Seilacher 1967; Seilacher 2007); Haentzschel (1975); Uchman (1995, 1998), and Monaco and Checconi (2008) were employed for identification and classification of the present ichnotaxa. .

4. Ichnotaxonomic analysis

Data in Table 1 illustrates a systematic description of the trace fossils identified in the Unit 2 of the Deh-Sufiyan Formation. Trace fossils were mostly studied in the field, and ichnotaxonomic analysis was complemented with the photographs and collected specimens. The repository of collected material is the Faculty of Science, Ferdowsi University of Mashhad. A brief description of all the trace fossils is presented separately in Table 1, providing information on the toponomy, preservation, size, environmental distribution, and likely ethology of the tracemaker. The ichnotaxa are listed alphabetically. The ichnotaxa stated in the facies description are also organized in the decreasing order of the abundance. The trace fossil assemblage is characterized by a high ichnodiversity with 33 ichnospecies belonging to 22 ichnogenera.

5. Sedimentary facies associations and trace fossil distribution

5.1. Shale/marl-dominated facies association (FA1)

Description: FA1 comprises, in a vertical alternation (5 to 25 m), of thick/massive calcareous shale, graded intra-skeletal packstone/grainstone, interbedded limestone and marl, siltstone, marl to shale or nodular lime mudstone (Fig. 4a). Locally, glauconite-bearing beds are developed. Parallel and hummocky cross beddings and wave-ripples dominate the graded intra-skeletal packstone to grainstone facies. Small basal scours and cross-lamination are common sedimentary features of the siltstone layers. As opposed to the siltstone layers, dark brown mudstones lack any sedimentary structures. The thin beds (< 10cm thick) show a low diversity ichnofossil association. Bioturbation in this facies is sporadically distributed, and the intensity levels are remarkably low. The ethological groupings represented in the suite are dominated by the activities of detrital grazers (e.g., *?Phycosiphon* and *Helminthopsis*), epichnial, rosette-like dwelling/feeding burrows (*Gyrophyllites* isp.), deep-tier deposit-feeding (*Chondrites* isp.), and simple deposit-feeding structures (*Planolites* isp.); see Fig. 4b-d. In few localities with more basinward facies, this association comprises black, organic-rich, fissile, carbonaceous shales. The graded packstone/grainstone beds include fragments of crinoids and trilobites as well as variable amounts of intraclasts, and peloids.

Interpretation: Sedimentary features of this association indicate deposition in low-energy, deep-water environmental setting (e.g., deep subtidal) with periodic emergence and sediment reworking by storms. Consequently, it is interpreted that the association was

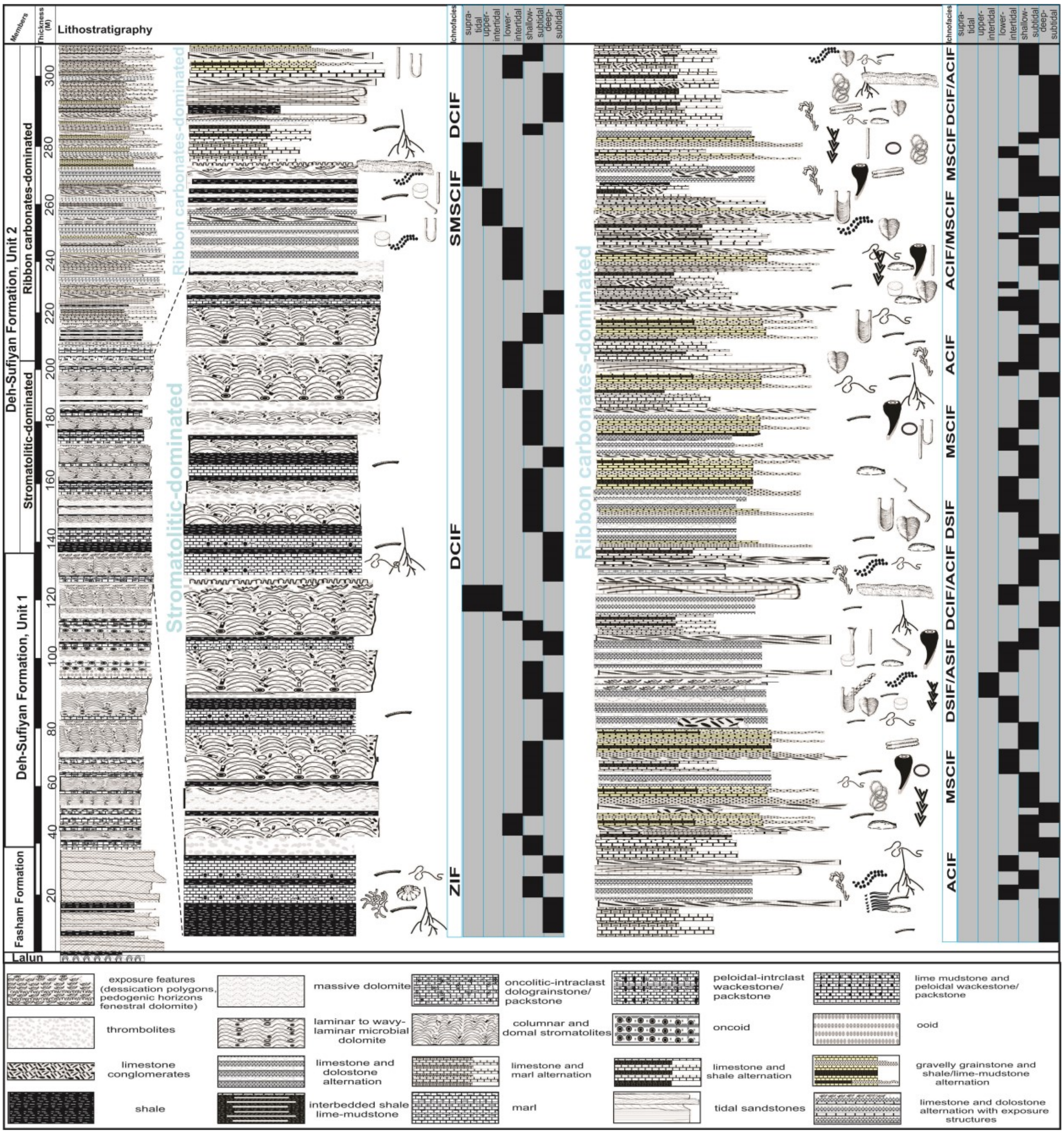

Fig 3. Stratigraphic sections measured at Shahmirzad showing the sedimentological characteristics and interpretation of the depositional environments of the Fasham and Deh-Sufiyan formations (Bayet-Goll et al. 2015a) associated with ichnological characteristics and ichnofacies: elements of ZIF: the *Zoophycos* ichnofacies, DCIF: stressed expression of the mixed *Skolithos-Cruziana* ichnofacies, SMSCIF: stressed expression of the mixed *Skolithos-Cruziana* ichnofacies, ACIF: the archetypical *Cruziana* ichnofacies, MSCIF: the mixed *Skolithos-Cruziana* ichnofacies, DSIF: distal expression of the *Cruziana* ichnofacies, ASIF: the archetypical *Skolithos* ichnofacies.

deposited in open-marine, outer ramp environment below storm wave base, where occasional storms deposit silty sediments from the shallow platform. The absence of fossils and the lack of sedimentary structures indicate that the massive calcareous shales have been deposited in a deep subtidal environment during increased clastic supply from close land areas. The trace fossil assemblage records grazing and foraging behavior and a less common occurrence of deposit feeders. This assemblage is indicative of the elements of the *Zoophycos* ichnofacies or, in some cases, a distal domain of the *Cruziana* ichnofacies, characterizing quiescent marine shelf environments, well below maximum storm wave base (Bann et al. 2008; Gingras et al. 2011a, b; Bayet-Goll et al. 2015a and 2016a).

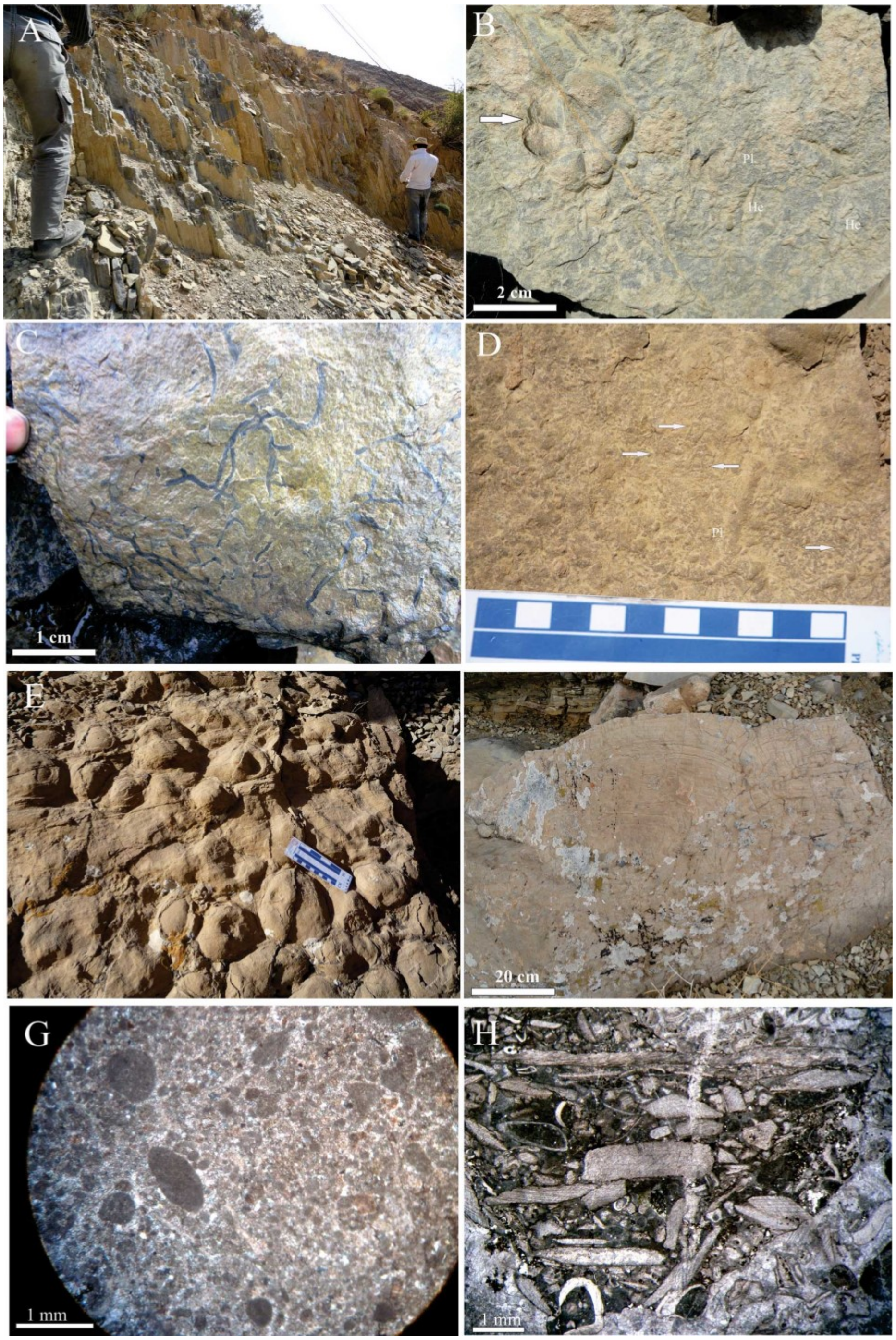

Fig.4.A) Field photographs of thick calcareous shale (FA1) in the lower part of units 1 of the Deh-Sufiyan Formation. B) *Gyrophyllites* isp., (arrow), *Planolites* isp. *(Pl)* and *Helminthopsis* isp.*(He)*inFA1. C) *Chondrites* isp. in FA1. D) *Phycosiphon* isp., (arrows), *Planolites* isp. *(Pl)* in FA1.e) Upper surface of low-relief, stacked, vertically and laterally linked hemispheroidal stromatolites with ooids, peloids, oncoids and intraclasts present in depressions between stromatolite heads (FA2). F) Domal stromatolites with irregular, wavy, or crinkly laminations stacked vertically and laterally linked. G) Peloidal-intraclast packstone/grainstone facies composed of peloids, micritic and well rounded to angular intraclasts, bioclasts with some oncoids (FA3). H) floatstones/rudstones facies association (FA4) with bioclasts such as trilobites, brachiopods, and echinoderms less frequently peloids, and intraclasts.

5.2. Microbialite facies association (FA2)

Description: Algal stromatolites, thrombolites with layers of dolomitized lime-mudstone, heterolithic shale/lime-mudstone and peloidal packstone/grainstone with minor skeletal material (trilobites and echinoderms) are common striking features in the lower part of the Unit 2. The stromatolitic build-ups are associated with peloids, intraclasts and calcispheres, locally with a grumelous or clotted texture, but with the absence of evident macrofauna. Several forms of microbial buildups in the Unit 2 include: 1) laminar to wavy-laminar; 2) domal or hemispheroidal; 3) giant domal; 4) bulbous; 5) columnar; 6) regular flabellate columns; and 7) unlaminated, loaf- to mound-shaped dolomitized thrombolites (Fig.4 e, f). The stromatolites demonstrate a gradual upward growth from the underlying sediment, generally with a sharp contact with the overlying sediments.

Interpretation: The succession, from wavy-undulose stromatolites, columnar stromatolites and domal stromatolites to stratiform stromatolites, demonstrates decreasing water turbulence from subtidal to intertidal environments (Glumac and Walker 2000). In this association the planar to slightly undulated types perhaps is formed in an upper intertidal flat, under relatively low-energy conditions, whereas the individual columnar stromatolite is interpreted to have been developed in an agitated intertidal setting (Tucker and Wright 1990). The low domed stromatolites, on the contrary, are indicative of less agitated-water, in a lower intertidal/shallow subtidal flat (Glumac and Walker 2000). Nonetheless, individual giant domal stromatolites embedded in lime-mudstone facies are interpreted as been formed in a shallow subtidal environment. The thrombolitic microbialites are interpreted to have been formed in a shallow subtidal environment, in close proximity to stromatolitic microbialites and dolomitized oncoids.

5.3. Bioturbated lime mudstone to packstone/grainstone facies association (FA3)

Description: This facies association is mainly made up of fenestral dolomitized lime mudstone, bioturbated lime mudstone with peloidal-clotted micrite and peloidal wackestone/packstone with planar laminae, heavily bioturbated peloid-intraclast packstone/grainstone represented by mottled texture and selective dolomitization of burrows and fine- to medium-grained bio-intraclastic grainstone/packstone with subordinate wavy microbial laminae (Fig. 4g). Vugs, desiccation cracks, tepee structures, and halite crystals are found in this facies. The limestone beds are greatly bioturbated with bioturbation index between 4 and 5, following Taylor and Goldring (1993). The trace fossil assemblage is dominated by *Skolithos*, *Arenicolites, Palaeophycus, Diplichnites*, *Bergaueria* and *Planolites*. Generally, the abundance of bioturbated structure in this facies association tends to decrease stratigraphically upward, while that of microbial laminations increases.

Interpretation: The above lithofacies are interpreted to have accumulated in supratidal to lower intertidal environments. The upward decrease in the relative proportion of bioturbated structures and the upward increase in microbial lamination within the lithofacies could well be associated with the slight environmental shift from a lower intertidal to upper intertidal/supratidal settings. The dolomitized lime mudstone indicates planar laminae, mainly produced by microbial community, perhaps cyanobacteria. An assemblage of dolomite and fenestral voids is a particularly good indicator for a supratidal to upper intertidal environment (Bayet-Goll et al. 2015a, 2016b). On the contrary, the abundant vertical and slightly inclined burrows in addition to low-diversity and abundant bioclastic grains suggest that the bioturbated limestone lithofacies was deposited in an intertidal environment. The trace fossil suite in the bioturbation-dominant lithofacies is indicative of a stressed mixed *Skolithos-Cruziana* ichnofacies (MacEachern et al. 2005, 2007a, b).

5.4. Floatstones/rudstones facies association (FA4)

Description: This facies association is made up of skeletal limestones including floatstones to coarse-grained grainstones to floatstones/rudstones facies, which comprises bioclasts such as trilobites, brachiopods, and echinoderms, and less often of peloids, intraclasts, silt or sand-sized quartz grains and glauconite (Fig. 4h). This facies association includes graded grainstone/floatstones layers, or floatstones to grainstone/rudstones layers with parallel-laminated, ripple cross stratification, hummocky and swaley cross-stratification. The sole of the beds are covered with pot and gutter casts (Fig.4h).

Interpretation: The sedimentological investigation suggests that this facies association was formed close to fair-weather wave base in a shallow-water, high-energy setting. Usually, the graded floatstones to grainstone layers are indicative of frequent reworking by currents and waves, above fair-weather wave base (e.g., shoal) (Palma et al. 2007), while the hummocky and swaley cross-stratified grainstones/rudstones and graded grainstone are distinctive of deposits reworked by storm-induced combined flows, below fair-weather wave base, but above storm wave base (e.g., shallow subtidal zones) (Myrow et al. 2004).

5.5. Ribbon carbonates facies association (FA5)

Ribbon carbonates in a millimeter-to centimeter-scale are a common and striking feature in the lower and upper part of the Unit 2. According to the composition and proportion of carbonate and argillaceous deposits, as well as the sedimentary structures, the ribbon rocks are grouped into: 1) Limestone and dolostone couplet (L-De); 2) Wavy/lenticular-bedded limestone and dolostone couplet (L-Dw); 3)Limestone and dolostone couplet with exposure structures (L-Di); 4) Graded grainstone and shale/dolomite couplet (Gg-S or Gg-Lm); 5) Limestone and marlstone couplet (L-M); and 6) Limestone and shale couplet (L-S) (Bayet-Goll et al. 2015a). A facies analysis of the ribbon carbonates, emphasizing the role of physical sedimentological data, has been given in (Bayet-Goll et al. 2015a). A combined lithofacies/ichnofacies scheme is presented in this study and more details of the ichnology are given below.

5.5.1. The ichnological attributes of the ribbon carbonates

Limestone and dolostone couplet (L-De): This couplet is characterized by bluish-grey limestone (wackestone and packstone) with yellowish-gray dolostone layers (dolomudstones) having a range of limestone-dolostone ratios, with lumpy, irregular to wavy- and lenticular geometries (Fig. 5a).Vugs, desiccation cracks, wrinkle structures, fenestral fabrics and halite crystals (Fig.5b) are found in this facies (Bayet-Goll et al. 2015a). The ichnofossils are distinctively small in size and of horizontal, simple feeding strategies of trophic generalists and facies-crossing ichnogenera. This facies is not strongly bioturbated and diversity of trace fossil is usually very low. Most of the units have little or no bioturbation, with the BI ranging from 0 to 1. The trace fossil assemblage is dominated by suspension-feeding structures (*Skolithos* isp., *Arenicolites* isp.), with a subordinate suite of dwelling/deposit-feeding to passive carnivores (*Bergaueria* isp., *Palaeophycus* isp.,), simple deposit-feeding structures (*Planolites* isp.) and locomotion (*Diplichnites* isp.) (Fig.5c, d). The abundance of bioturbated structures in this facies is likely to decrease stratigraphically upward, while that of desiccation cracks, fenestral microbial dolomite, and evaporite casts increases.

Interpretation: This couplet was interpreted as intertidal to supratidal deposit. Sedimentary characteristics of the L-De couplet are a product of intermittent sedimentation and erosion in an environment exposed to periodic traction currents and sedimentation of fines from suspension. The upward-decrease in the relative proportion of bioturbation and the upward-increase in fenestral microbial dolomite could be connected with an environmental shift from an intertidal to a supratidal setting. The trace fossil suite represents a stressed expression of the *Skolithos* ichnofacies (MacEachern et al. 2005, 2007b; Bayet-Goll et al. 2015b). The largely unburrowed nature of the L-De couplets with sporadic distributions of burrowing, smaller size of ichofaunas, containing simple feeding strategies of trophic generalists, facies-crossing ichnogenera, and the scarcity of diverse and robust trace fossil suites indicate temporal persistence of physico-chemical conditions. The most significant environmental factors deterring infaunal burrowing in intertidal to supratidal settings are perhaps changing salinity and fluctuating temperature of the water column. The abundance of the evidence of subaerial exposure in the L-De couplets provide further evidence of an ichnologically stressed environment during the deposition.

Limestone and dolostone couplet (L-D): In this couplet, limestone layers vary in grain size and composition and form repetitive fining-upward layers that range from grainstone to lime mudstone. The dimension and relative abundance of the HCS and SCS, planar lamination and combined-flow-ripple cross-stratification connected with bed thickness, grain size and the trace fossil assemblage, appear to show great variation based on ideal tempestite sequence and proximal-to-distal, wave-dominated combined flow marine ramp sequence (Bayet-Goll et al. 2015a). Under these conditions, the L-D couplets described herein show three main subfacies (L-D1, L-D2, L-D3 couplets), characterized by different styles of ichnodiversity and bioturbation intensities and bedding (Fig.5e-g).

Ichnodiversity and bioturbation intensities in the L-D2 and L-D3 couplets are usually high, with intervals totally or nearly completely homogenized by bioturbation. The ethological groupings represented in the suite are dominated by suspension-feeding structures (*Diplocraterion* isp., *Skolithos* isp.), dwelling/deposit-feeding to passive carnivore behaviors (*Palaeophycus tubularis*), with subordinate suite of simple deposit-feeding structures (*Planolites* isp., *P. beverleyensis*), surface detritus-feeders (*Rosselia* isp.), and locomotion (*Diplichnites gouldi* and *Monomorphichnus* isp.). Bioturbation in the L-D1 couplets is mostly limited to bedding planes and internal bioturbation is sparse. Burrows are usually restricted to the surface of the layers with a low abundance mixed trace fossil suite of suspension-feeding structures (*Diplocraterion* isp., *Skolithos* isp.), resting (*Lockeia* isp., *Bergaueria* isp.), dwelling/deposit-feeding to passive carnivore behaviors (*Halopoa* isp., *H. annulata,*), with subordinate suite of surface detritus-feeders (*Rosselia* isp., *R. socialis*) and fugichnia (Fig.5h-j and Fig.6 a-c). Locally, predominant forms include *Rosselia* isp., which are usually vertically stacked, showing equilibrium adjustment in response to episodic sedimentation. Where the degree of bioturbation is high, the trace fossil assemblage is usually dominated by one ichnospecies (*Diplocraterion* isp.). Such forms include high density of basal parts of U-shaped dwelling burrows of suspension feeders (*Diplocraterion*), and are believed to represent the dwelling of an opportunistic colonization (Bayet-Goll et al. 2016a, b).

Interpretation: L-D couplets in the ribbon rocks are interpreted as storm-reworked deposits, that are produced as high-energy deposits of subtidal environments below and close to fairweather wave base (FWWB) with oxygenated sea water conditions and

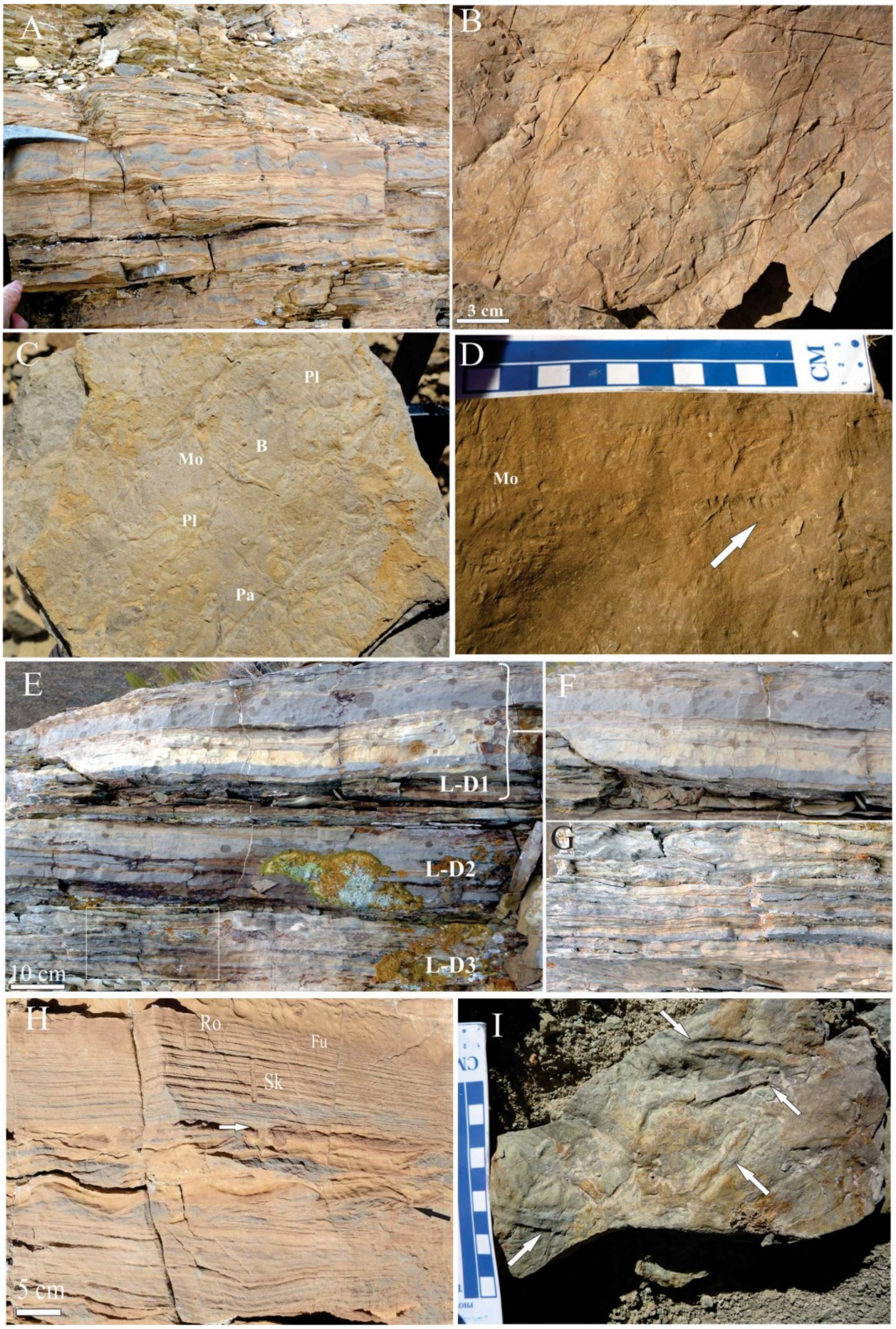

Fig.5.A) L-De couplet shows a range of limestone-dolostone ratios with wavy- and lenticular geometries. B) Vugs and halite crystals in L-De couplet. C) *Palaeophycus* isp. *(Pa), Planolites* isp. *(Pl), Bergaueria* isp. *(Be)* and *Monomorphichnus (Mo)* in L-De couplet. D) *Diplichnites* isp., (arrow) and *Monomorphichnus (Mo)* in L-De couplet. E, F, G) L-D couplets with three main facies (L-D1, L-D2, L-D3 couplets), characterized by different style of bedding, associated with a trend of increasing width/thickness ratios of HCS and combined-flow ripples (L-Dw→ L-D3→ L-D2→ L-D1). H) L-D1 couplets, the beds are commonly graded including HCS, parallel lamination, quasi-planar lamination and combined-flow ripples (black arrow) associated with *Skolithos* (Sk), *Rosselia* (Ro) and fugichnia (Fu). I) *Palaeophycus tubularis* (arrows) .

Fig.6. a) *Halopoa annulata* in L-D couplets. B) *Halopoa* isp. in L-D couplets. C) *Diplichnites gouldi* (Di) and *Monomorphichnus (Mo)* in L-D couplets. D) Wavy/lenticular-bedded limestone and dolostone couplet (L-Dw) couplets, the beds are commonly graded with L-D3 couplets. E) *Rusophycus carbonarius* in L-Dw couplets. F) *Didymaulichnus* isp. in L-Dw couplets. G) *Lockeia* cf *siliquaria* in L-Dw couplets. H) *Monocraterion* isp. in L-Dw couplets. I) Gg-Lm couplets, the beds are graded with lower divisions of curved scour surfaces and gutter cast and basal lags into micro-HCS and parallel lamination. J) Gg-S couplets, the beds are graded and contain curved scour surfaces and parallel lamination, large-scale HCS associated with fugichnia (arrows).

normal salinity as a result of the common presence of bioturbation and fossils (Bayet-Goll et al. 2014, 2015a). The spatial arrangement of the L-D1, L-D2 and L-D3 couplets and their character of storm bed sequences along the depth-related environmental gradients point to the significance of water energy as one of the major control factors affecting distribution patterns of the succession of sedimentary structures. Variations in the thickness and character of sedimentary structures can be used to tease out proximal–distal trends (Ito et al. 2001). Thinner distinct hummocky beds with rippled tops in the L-D2 and L-D3 couplets, separated by dolomudstones interbeds, represent storm reworking below FWWB. On the contrary, the thicker amalgamated planar lamination and hummocky beds signify storm reworking close to FWWB (Bayet-Goll et al. 2014, 2015a).

The overall trace fossil assemblage in the L-D2 and L-D3 couplets is interpreted to display elements of a distal *Skolithos* ichnofacies (MacEacherrn and Bann 2008). Within this facies, more proximal deposits are probably represented by the distal expression of the *Skolithos* ichnofacies, while more distal deposits are represented by a very diverse, proximal expression of the *Cruziana* ichnofacies. The absence or scarcity of deposit-feeding and grazing structures are probably as a result of the removal by erosion rather than absence of deposition [2], because of the rapid deposition of the sediment and turbidity in these environments, trace makers might have a little time left to significantly bioturbate the sediment before overlying beds are deposited (MacEacherrn and Bann 2008). On the contrary, the general trace fossil assemblage in the L-D1 shows the activities of a community of opportunists and resilient members of the ambient suite, and is characteristic of elements of the archetypical *Skolithos* ichnofacies. High sedimentation rates and erosion resulting from continuous and more intense reworking of tempestites or from high magnitude of physical reworking are believed to be responsible for the scarce bioturbation and an abundance of vertical domichnia (Bayet-Goll et al. 2014, 2015a). The paucity of deposit-feeding structures in these deposits is probably caused by the abundance of well-winnowed sand, and the general paucity of endobenthic food for deposit feeders.

Wavy/lenticular-bedded limestone and dolostone couplet (L-Dw): This subfacies is closely related to the L-D3 couplets and is represented by crudely laminated, limestone with dolostone layers. These interlayered rocks grade from wavy- and lenticular-bedded ribbon-rocks to lumpy, irregular and nodular varieties. This couplet is volumetrically dominated by graded lags in base, the HCS and micro-HCS, combined-flow-ripple cross-stratification and horizontally laminations (Bayet-Goll et al. 2015a), (Fig. 6d). The finer-grained interbeds are fairly bioturbated and the different suite of trace fossils comprise locomotion (*Didymaulichnus* isp.), resting (*Lockeia* cf *siliquaria* and *Rusophycus carbonarius*), and dwelling/deposit-feeding to passive carnivore (*Palaeophycus* isp.). Structures produced by feeding and grazing burrows of vagrant organisms such as *Helminthopsis* isp., *Planolites* isp., and meandering cylinders are locally abundant. On the other hand, the thicker beds range from unbioturbated to slightly bioturbated (Fig. 6e-g). These beds contain the deeply penetrating, vertical domiciles of suspension-feeding organisms (*Skolithos* isp., *?Monocraterion* isp.), local occurrences of the vertical dwellings of suspension-feeding organisms (*Diplocraterion* isp.), and fugichnia (Fig. 6h).

Interpretation: The gradational contact between the L-D3 and L-Dw couplets implies that the two intervals are genetically related (Bayet-Goll et al. 2015a). The rhythmically interstratified bioturbated finer-grained interbeds and sharp-based beds displaying the HCS and micro-HCS show the alternation of slow fair-weather mudstone deposition with storm-emplaced beds on a transition-zone environment below FWWB. The L-Dw couplets are not interpreted as burrowed intertidal deposits because mudcracks, fenestrae or other characteristic features of tidal-flat deposition are totally absent (Goldhammer et al. 2013).

This couplets is made up of suites attributable to the elements of the *Skolithos* ichnofacies, dominated by vertical domichnia and resilient surface detritus-feeders alternating with subordinate deposit-feeding structures of the *Cruziana* ichnofacies. These suites are differentiated from the entirely marine proximal expressions of the ichnofacies by the impoverishment of specific structures, paucity of deposit-feeding, grazing structures, and the abundance of opportunistic suspension-feeding organisms, as well as by an overall lower diversity. On the other hand, the periods between storms in the L-Dw couplets (also L-D couplets) may have been too short to allow the activity of trace makers of deposit-feeding, grazing structures (Bayet-Goll et al. 2015a).

Graded grainstone and shale or lime-mudstone couplet (Gg-S or Gg-Lm): In these couplets, limestone layers vary in grain size and composition and form graded rhythmite beds (Fig. 6i-j). The graded rhythmite beds demonstrate an upward increase in spacing, but a decrease in grain size and thickness of limestone laminae. The Gg-Lm couplets are closely associated with the L-D3 and L-Dw couplets. On the contrary, the Gg-S couplets are closely related to the L-M1 couplets. In these couplets the dimension and thickness of the HCS and combined-flow-ripple cross-stratification connected with bed thickness, grain size and basal lags, appears to show a trend of reduction with increasing palaeo-water depth (Bayet-Goll et al. 2015a).

These couplets are characterized by highly variable ichnodiversity and bioturbation intensities, ranging from mottled beds to sparsely to unburrowed beds. The trace fossil suite can be subdivided into one associated with shale or lime-mudstone beds, and one showing infaunal colonization of the grainstone units. The basal erosion parts in the limestones layers are less strongly bioturbated and are dominated by suspension-feeding structures (*Skolithos* isp., *Diplocraterion* isp.), open dwelling burrow of a suspension feeder or predator as passive carnivore (*Palaeophycus* isp.), surface detritus-feeders (*Rosselia* isp.), and fugichnia (Fig. 7a-b). The thicker amalgamated beds are not burrowed, or contain sparse, top-down bioturbation, or are sparsely burrowed with fugichnia and *Skolithos* isp. (Fig. 7c). Locally, the trace-fossil suite in the tempestite beds is dominated by the vertical, heavily spreiten-bearing burrows of small, opportunistic, suspension-feeding organisms (*Diplocraterion* isp.) (Fig. 7d). On the contrary, bioturbation in the finer-grained interbeds is locally intermittent, decreasing in intensity when compared to the mudstone beds. In spite of the sporadic distribution and low degree of bioturbation, the general diversity of the trace-fossil suite is high. Characteristic ichnogenera are uniformly distributed all through the facies, and include abundant locomotion (*Diplichnites* isp.), bilobate traces preserved as rounded convex hypichnia with marked transverse (*Rusophycus carbonarius*), and grazing/foraging behaviors (*Helminthopsis* isp., meandering cylinders). The less common elements are intermittently distributed, and include short lived resting traces of small burrowing bivalves (*Lockeia* cf *siliquaria*), hypichnial mounds (*Bergaueria* isp.) and horizontal, simple feeding strategies of facies-crossing ichnogenera (such as *Planolites beverleyensis, Palaeophycus* isp.). The uncommon elements include crawling trail recording the activity of an infaunal bilaterally symmetrical trace-maker (*Didymaulichnus* isp.), and deposit-feeding structures, such as *Circulichnus* isp. (Fig. 7e-g).

Interpretation: The general size grading and sequence of structures in these couplets are interpreted as storm deposits under decelerating flows, above strorm weather base (Bayet-Goll et al. 2015a). Winnowing and suspension of finer sediments by turbulence of storm results in the deposition of upward-fining, but characteristically distinctly segregated coarse (lag) and fine (suspended fraction) couplets (Kwon et al. 2002). The abundance of wave-formed structures and excellent preservation of tempestites demonstrate deposition above storm wave base, but below fairweather wave base. In storm-dominated intervals of the Gg-S and Gg-Lm couplets, the ichnological signatures are different, when protected from storm erosion; these intervals could display maximum activity of trace makers. The mixtures of grazing/foraging, deposit-feeding, and suspension-feeding structures are indicative of the elements of the mixed *Skolithos-Cruziana* ichnofacies (Bayet-Goll et al. 2015b, 2016a). Ethologically, suites attributable to the *Cruziana* ichnofacies record the activity of infaunal organisms that burrowed through the fair weather and waning mudstone down to the limestone-shale interface (MacEacherrn and Bann 2008). However, reworking of the substrate by high-energy waves in graded rhythmites mostly prevents burrowing, with the exception of opportunistic suspension-feeding organisms that ethologically, are attributable to the *Skolithos* ichnofacies (MacEacherrn and Bann 2008). The variable intensity of burrowing and the trace fossil assemblage resulted from differences in the physical character of the substrate. Consequently, these couplets are usually identified as: 1) the alternation of (graded) limestone layer with elements of opportunistic dwelling burrows of the *Skolithos* ichnofacies as distal storm deposits and 2) a clayey layer or dolomitized lime mud as background deposits, with elements of resident fair-weather populations of the *Cruziana* ichnofacies, respectively.

Limestone and marlstone couplet (L-M): The L-M couplets are transitional ones between the Gg-S/Gg-Lm and L-S couplets, but are distinct enough from both to be separated (Bayet-Goll et al. 2015a). The strata of the L-M couplets alternate between laminated beds (L-M1) and homogenous beds (L-M2) (Fig. 7h-i). The latter majorly comprises lumpy and irregular varieties of light greenish marlstone layer with thin, light gray, laterally extensive, erosive-based, limestone beds with parallel lamination, wavy ripple cross-lamination and symmetrical to near-symmetrical rippled tops (Bayet-Goll et al. 2015a). Locally, the limestone layers in the couplets are typically homogeneous and occasionally crudely laminated (L-M2).Bioturbation in the marlstone beds is mostly constrained to bedding planes and internal bioturbation is sparse. In some cases, the trace fossils normally overprint a very mottled bioturbated texture. Burrows are restricted normally to the surface of the layers with a low abundance mixed trace fossil suite of resting (*Rusophycus carbonarius, R. didymus, R. eutendorfensis,Lockeia* cf *siliquaria, Bergaueria* isp.), trackways made up of two rows of imprints (*Diplichnites*isp. and *Monomorphichnus* isp.), locomotional-foraging trails of a vagile, bottom-living trace maker, (*?Cruziana* isp.), and grazing trails produced by deposit-feeding organisms, perhaps polychaete annelids (*Helminthopsis abeli, Gordia,* isp.). The less common elements are intermittently distributed, and comprise resting (*Bergaueria* isp.), horizontal, simple feeding strategies (*Planolites* isp., *P. montanus* and *Palaeophycus* isp.), and vertical dwellings of suspension (*Skolithos* isp.).The uncommon elements comprise locomotion (*Didymaulichnus* isp.), zigzag traces of shallow deposit-feeders (*Treptichnus* isp.), infaunal deposit-feeders related to chemo-symbiotic behaviour such as *Chondrites* isp. (living at the aerobic/anoxic interface), dwelling structure of filter feeding organisms (?*Rosselia* isp.), and deposit-feeding structures (*Circulichnus* isp.) (Fig. 7j and Fig. 8).

Fig.7. A) *Skolithos* isp (Sk) *Diplocraterion* isp. (Di) and *Arenicolites* isp. (Ar) in Gg-Lm couplets. B) *Rosselia* isp. in Gg-Lm couplets. C) Gg-S couplets, the beds are graded and contains basal lags with curved scour surfaces and gutter cast, parallel lamination large-scale HCS associated with *Skolithos* (Sk) and fugichnia (Fu), (Bayet-Goll et al. 2015a). D) *Diplocraterion* isp. in Gg-Lm couplets. E) Mottled texture with meandering cylinders in Gg-S couplets. F) *Gordia*isp. (Go) with *Planolites beverleyensis (Pl)* in Gg-S couplets. G) *Circulichnus* isp. in Gg-S couplets. H, I) The strata of L-M couplets alternate between laminated beds (L-M1, I) and homogenous beds (L-M2, h). J) *Rusophycus eutendorfensis* (Ru) and *?Treptichnus* isp. (arrow) in L-M couplets.

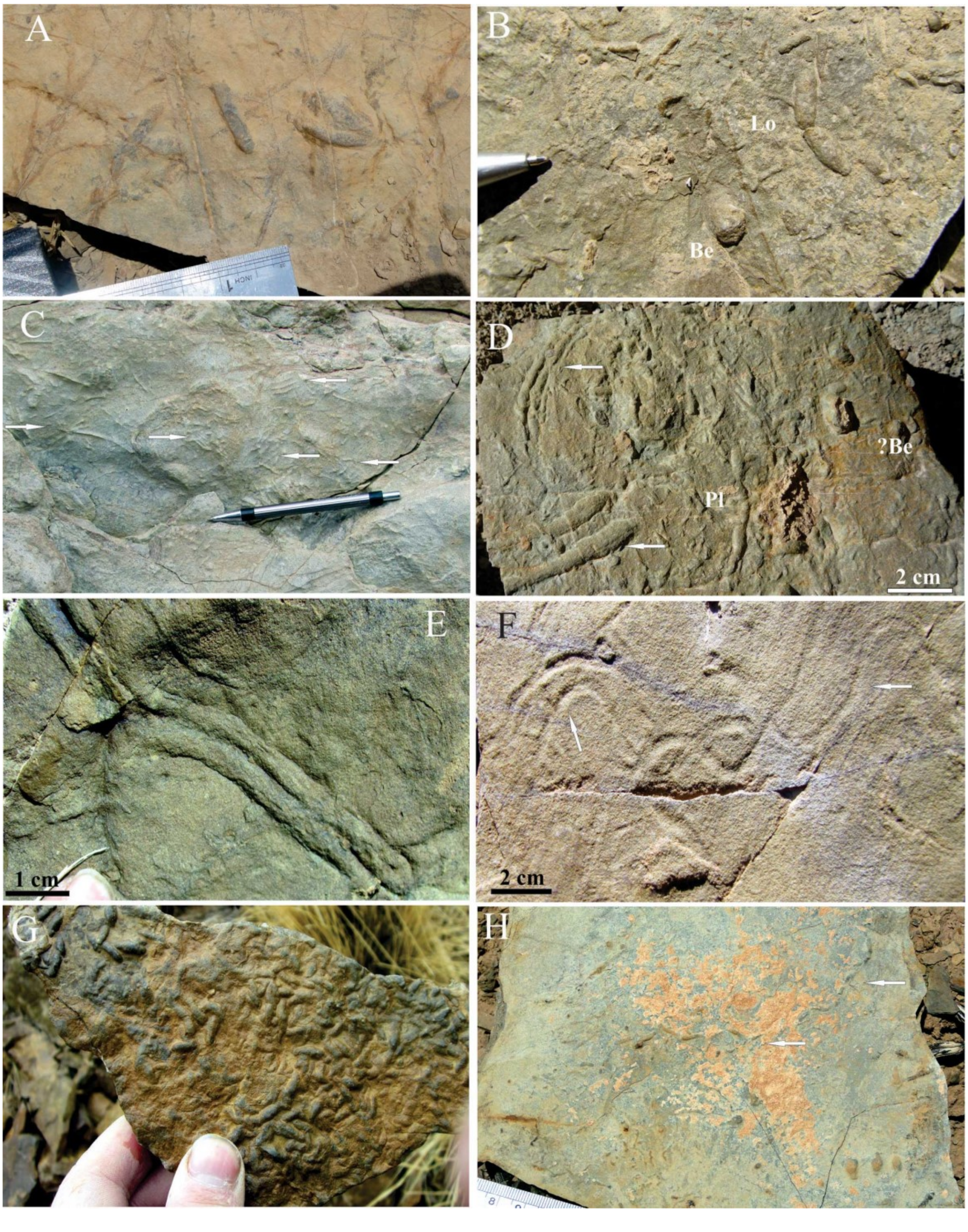

Fig.8. A) *Rusophycus didymus* inL-M couplets. B) *Lockeia* cf *siliquaria* (Lo) and *Bergaueria* isp. (Be) in L-M couplets. C) *Monomorphichnus (Mo)* in L-M couplets. d) *Cruziana* isp. (arrow) *Planolites* isp. *(Pl), ?Bergaueria* isp. (Be) inL-M couplets. E) *Cruziana* isp. In L-M couplets. F) *Helminthopsis* isp. in L-M couplets. G) *Planolites montanus* in L-M couplets. H) *Treptichnus pedum* in L-M couplets.

Interpretation: The L-M1 couplets signify deposition of thin limestone beds from waning, storm-generated currents, interbedded with fair-weather suspension-deposited marlstones (as suspended fines settled from suspension under waning storm-energy conditions) in a deep subtidal environment above and close to storm wave base. On the contrary, low-energy conditions occurred during the deposition of the homogeneous L-

M2 couplets, resulting in sedimentation as a result of the settling of carbonate mud and argillaceous mud from suspension below storm wave base (Bayet-Goll et al. 2015a).

The diverse trace fossil assemblage of the L-M couplets is characteristic of the elements of the archetypical *Cruziana* ichnofacies and shows accumulation in a subtidal environment under the action of waves as a result of sporadic storms and sediment fallout (Angulo and Buatois 2012). The archetypical Cruziana ichnofacies reflects quiescent conditions with cohesive soft substrates, reduced rates of deposition, and variable but abundant food resources (MacEacherrn and Bann 2008; Bayet-Goll et al. 2015b). The highly diverse trace fossil suite (although with very low abundance) is dominated by a combination of complex deposit-feeding, detritus-feeding, locomotion, resting, grazing and foraging structures with less common vertical structures. In this ichnofacies, most burrows in the L-M couplets show surface grazing and deposit-feeding behaviors on soft, cohesive substrates, typical of quiet-water and entirely marine conditions that experienced lengthy periods of fairweather settling from suspension, below and close to storm wave base. The vertical burrows that represent the dwellings of suspension-feeding organisms correspond to the opportunistic colonization in storm beds.

Limestone and shale couplet (L-S): The L-S couplets mainly include nodular and irregular varieties. These couplets are characterized by massive, cross- or parallel laminated limestone beds with significant lateral extent, interbedded with dark gray shale or dolomitic shale layers (Fig. 9a). The couplets demonstrates considerably low bioturbation intensity and diversity. Locally, the limestones are slightly bioturbated with intermittent burrows. In some cases, the trace fossils normally overprint a very mottled bioturbate texture (Fig. 9b). The ethological groupings represented in the suite are dominated by grazing behaviors (*Helminthopsis* isp. and *Planolites* isp., *P. montanus*), with subordinate suite of resting (*Rusophycus carbonarius*), and deep-tier deposit-feeding (*Chondrites* isp.) behaviors (Fig. 9c-d).

Interpretation: The overall fine-grained nature of these couplets represents deposition in a relatively quiescent environment. The massive limestone and shale show deposition by suspension fallout in a low-energy environment, while the cross- or parallel laminated limestone intervals were deposited by weak traction currents.

The trace fossil suite of the L-S couplets reflects the elements of a distal expression of the *Cruziana* ichnofacies and shows deposition in a low-energy deep subtidal environment, usually below and close to storm wave base (MacEacherrn and Bann 2008; Angulo and Buatois 2012). This ichnofacies demonstrates an increase in the proportions of grazing structures and chemo-symbiotic activities. Similarly, unlike the L-M couplets, the basinward suites of the L-S couplets display less locomotion, resting, feeding and dwelling traces. The presence of fine-grained substrates with local soupy texture mostly favoured surface grazing, foraging and deep-tier deposit feeding, and is perhaps more significant environmental factor deterring deposit-feeding behaviours within the couplets (Bayet-Goll et al. 2014).

6. Discussion

6.1. Depositional system

A wide variety of stromatolite morphologies is found in the stromatolitic unit including laminar to wavy-laminar, domal or hemispheroidal, giant domal, bulbous, columnar, and regular flabellate column forms and unlaminated, loaf- to mound-shaped thrombolites (Bayet-Goll et al. 2015a). The extensively distributed thick microbial buildups formed an extensive intertidal-subtidal microbial flat under optimal conditions of water depth, sunlight, temperature, nutrient availability, and salinity. This environmental setting is supported by the presence of thrombolites in the subtidal environment, and by their association with shale/marl-dominated facies association in the subtidal environment. The upward variations in the macrostructures from thrombolites, columnar stromatolites, domal stromatolites, to microbial laminites or stratiform stromatolites and the incorporated intertidal environment bioturbation-dominant lithofacies indicate a shallowing water depth and a high-energy setting (Fig. 10a) (Glumac and Walker 2000).

Seven types of the ribbon carbonates are recognized based on sedimentary structures, ichnofacies, and bed geometry, which represent deposits during different phases of storm-induced depositional processes. Tempestite beds of the Deh-Sufiyan Formation show great variation in thickness, grain size and internal structures, depending mostly on the proximality–distality trends (Bayet-Goll et al. 2015a). Tempestite beds in the ribbon unit of the Deh-Sufiyan Formation depict a transgressive, proximal-to-distal, wave-dominated combined-flow marine ramp sequence, as recorded in the stratigraphic changes of: (1) the character of storm bed sequences; (2) relative abundance of the HCS; (3) propensity to amalgamate; (4) bed thickness and grain size; (5) frequency of tempestite events; and (6) ichnologic and trace fossil diversity (Bayet-Goll et al. 2014, 2015a). The vertical stratification successions from individual storm events show deposition during increasing combined oscillatory and unidirectional flows succeeded by the waning stages of a storm (Fig. 10b).

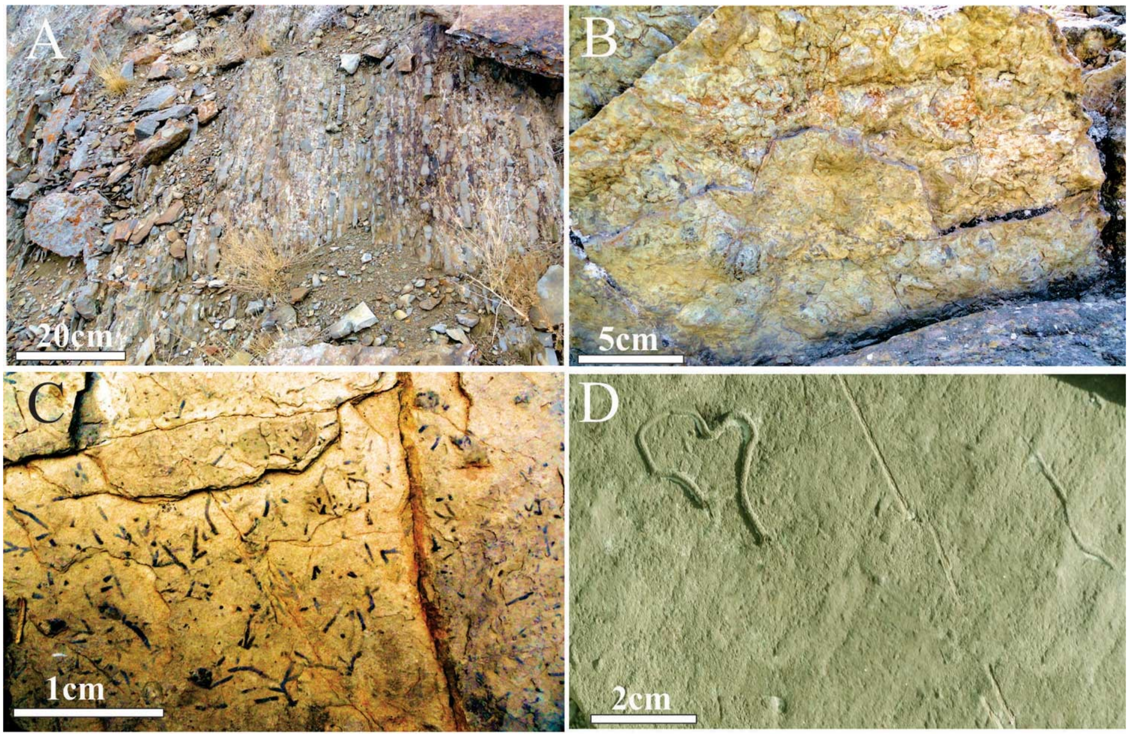

Fig 9.A) Limestone and shale couplet (L-S) contains limestone beds, interbedded with dolomitic shale layers. B) Mottled texture in L-S couplets. C) *Chondrites* isp. In L-S couplets. D) *Helminthopsis abeli* in L-S couplets.

6.2. Paleoecological implications: factors regulating ichnofaunal distribution

Ichnofossil assemblages and their features (size, diversity, bioturbation intensity, distribution and distribution style) that hold the greatest potential to improve paleoenvironmental interpretations allow for the development of a conceptual model that permits significantly more refined recognition and differentiation of lithofacies and successions in shallow marine regimes. Trace fossils record the behavior of their producers, typically as a response to subtle differences in environmental parameters such as substrate composition and consistency, availability and distribution of food, salinity, energy conditions, and oxygenation (Buatois et al. 2002; Bayet-Goll et al. 2015b). The trace fossil distribution and composition of ichnological assemblages are strongly connected with the degree of stability and temporal persistence of physico-chemical conditions in a sedimentary environment; highly diverse suites record optimal conditions, while low-diversity suites demonstrate environmental stress (Pemberton et al. 2001; Gingras et al. 2011a, b). The identification and interpretation of ichnological signatures and the spatial arrangement of sedimentary structures in the successions of this study can be used to further refine sedimentary interpretations of parameters such as wave energy, properties of substrate, the nature of the available food supply, variability in the rates of sedimentation and proximal-distal trends of the wave-dominated ramp. Considering the obvious deepening of the shallow marine depositional systems of wave-dominated complex parts of the ramp, the succession archetypal ichnofacies can express a bathymetric trend from deeper to shallower parts, and from higher-to-lower hydrodynamic condition of shallow marine depositional systems of the Unit 2 of the Deh-Sufiyan Formation.

The trace fossil assemblage related to the *Cruziana* ichnofacies is the most diverse and include more varied behavioral strategies. Ethologically, this assemblage comprises locomotion, resting, grazing, deposit-feeding, deep-tier deposit-feeding, dwelling/deposit-feeding to passive carnivore and dwelling structures of deposit-feeders or surface detritus-feeders (Table1). On the contrary, the trace fossil assemblage related to the *Skolithos* ichnofacies may have been produced by opportunistic organisms (r-strategists). Ethologically, this assemblage consists of suspension-feeding structures, passive carnivores, escape structures, and dwelling structures of deposit-feeders (Table1). As presented in Figure-3 and 10, the character of ichnological suites developed in the succession's archetypal ichnofacies and departures from it varies considerably. Resolving the ichnological signature of these stressed sedimentary settings is vital for reconstructing the depositional environment (MacEachern et al. 2007a, b).

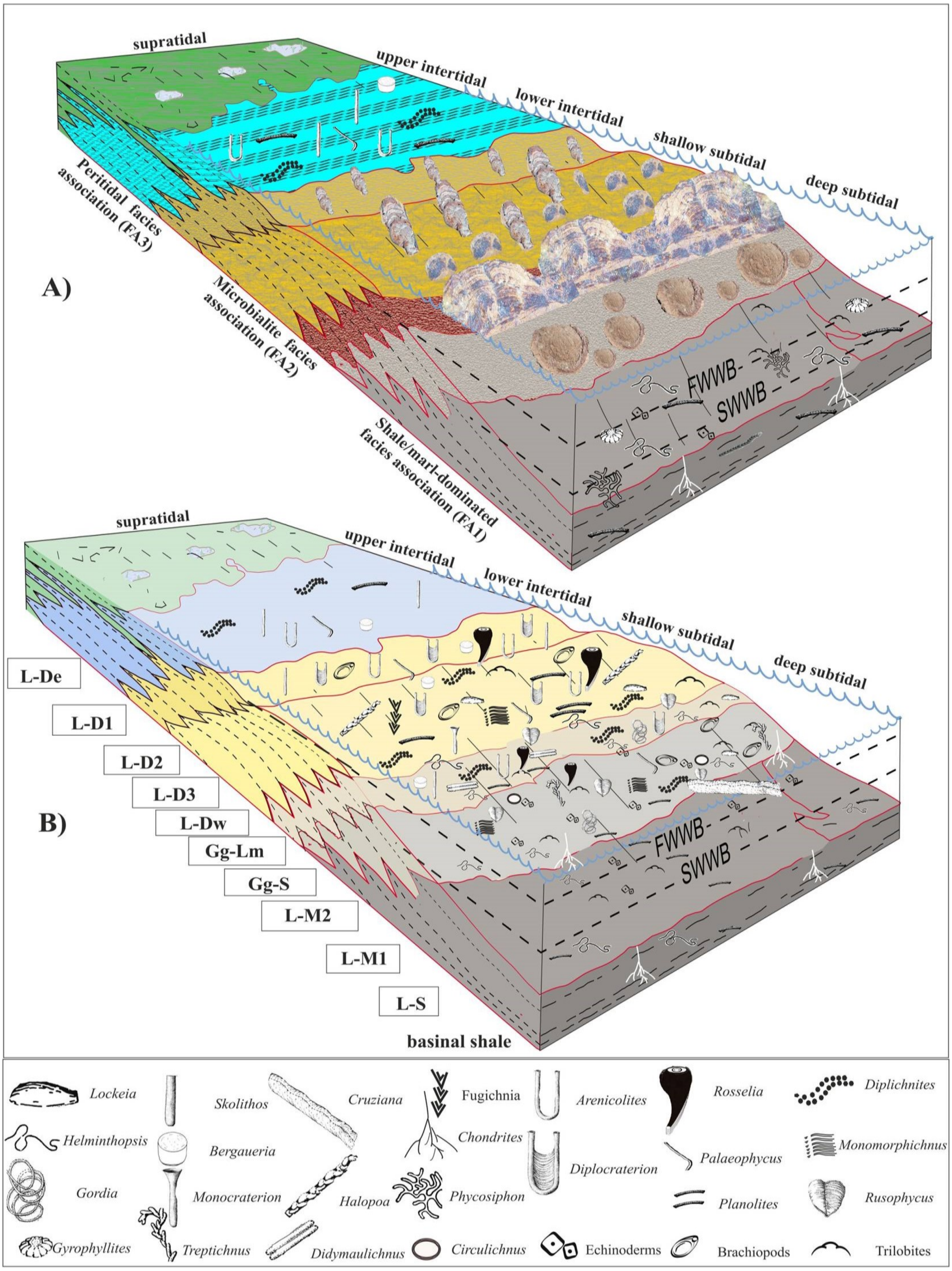

Fig.10. Palaeoenvironmental reconstruction of the geometry and facies/trace fossils distribution of unit 2 of the Deh-Sufiyan Formation, contains extent and a complex vertical succession of subtidal and peritidal lithofacies a) Stromatolitic unit and b) Ribbon unit.

The "stressed"character of the resulting ichnological suites or departures from the archetypal ichnofacies records the dynamic relationship between storm events, and high-energy wave-dominated coastal settings (Pemberton et al. 2001).

Storm-dominated settings as a result of physical stress affecting the depositional environment usually produce biogenically reworked substrate, which contains ichnological suites that represent opportunistic colonization in the storm bed, overprinted by a fair-weather suite typical of an equilibrium community and continuous sedimentation. These suites from the paleoenvironmental perspective are divided into an opportunistic event bed "suite" (or post-depositional) and a post-storm, fair-weather community "suite" (or predepositional). The fair weather trace fossil assemblage is the most diverse one and comprises more varied behavioral strategies, representing the elements of the *Cruziana* ichnofacies. Ethologically, this assemblage comprises locomotion (*Diplichnites* and *Didymaulichnus*), resting (*Rusophycus*, *Lockeia*, *Bergaueria*), grazing (*Planolites, Helminthopsis, Gordia, Scolicia*), deposit-feeding (*Circulichnus, Treptichnus*), deep-tier deposit-feeding (*Chondrites*), dwelling/deposit-feeding to passive carnivore (*Palaeophycus tubularis*) and dwelling structures of deposit-feeders or surface detritus-feeders (*Rosselia socialis*). The storm-related assemblage (or post-depositional) produced by opportunistic organisms (r-strategists), represents elements of the *Skolithos* ichnofacies. Ethologically, this assemblage consist of suspension-feeding structures (*Diplocraterion, Skolithos, Arenicolites* and *Monoceraterion*), passive carnivores (*Bergaueria*, *Palaeophycus*), escape structures (fugichnia), and dwelling structures of detritus-feeders (*Rosselia socialis*).

The suite in distal tempestites is characteristic of the archetypical *Cruziana* ichnofacies, distal expression of the *Cruziana* ichnofacies and the *Zoophycos* ichnofacies. The broadest range of ethologies and ichnogenera diversities of the archetypical *Cruziana* ichnofacies in the L-M2 and L-M1 couplets demonstrate depositional settings characterized by cohesive soft substrates, normally reduced the rates of deposition, and variable but abundant food resources (MacEachern et al. 2007; Gingras et al. 2011a, b). The highly diverse trace fossil suite, dominated by a mixture of complex deposit-feeding, detritus-feeding, grazing and foraging structures in the L-M2 and L-M1 couplets, indicates low rates of sedimentation, relatively stable substrate, sufficient nutrient supply and the presence of oxygen close to the sediment–water interface caused by the mixing of water by waves. Basinward, in distal tempestites and basinal settings (FA1 and L-S couplets), under depositional conditions favoured the suites of distal *Cruziana* ichnofacies and the *Zoophycos* ichnofacies, substrates are fine-grained and soupy, and trace fossil diversity is reduced (with low to moderate abundance of burrows and sporadic distribution), due to the reduced variation in food resources and the presence of substrates that produce favourable conditions for surface grazing and deep-tier deposit feeding (MacEacherrn and Bann 2008; Gingras et al. 2011a, b). In spite of an extensive environmental range, these ichnofacies are generally connected with deposition in poorly oxygenated, organic rich, quiet-water settings below storm wave base. The low oxygen concentrations in the bottom and interstitial waters affected the size of trace fossil, burrow diameter, abundances, and diversity. On the other hand, the suite in the Gg-S, Gg-Lm couplets shows different ichnological signatures including mixtures of grazing/foraging, deposit-feeding, and suspension-feeding structures with high diversity. Fluctuating energy level of the water column greatly affects the preserved ichnofacies, in that low-energy (fair-weather) suites, and recolonization (post-event) behaviors are preserved. The suite attributed to *Cruziana* ichnofacies represents infaunal reworking of the substrate during fair-weather. Most of the tempestite-related physical structures, however, represent storm deposition, especially the HCS and graded layers. Development of such structures results in the introduction of physical changes to the substrate, including modification of sediment grain size, sediment consistency, and compaction. Consequently, in such conditions, the suite (associated with HCS units) is dominated by vertical burrows of opportunistic suspension-feeders, resilient surface detritus-feeders and passive carnivores, and is indicative of the *Skolithos* ichnofacies. Such recurring alternations have been named the mixed *Skolithos-Cruziana* ichnofacies (Pemberton and MacEachern 1997). Therefore, this alternation of ichnofacies in intermediate settings of this study is usually attributed to the fluctuations in hydrodynamic energy (MacEacherrn and Bann 2008; Gingras et al. 2011a, b). The suites in the L-D and L-Dw couplets contain elements of the distal *Skolithos* ichnofacies and the archetypal *Skolithos* ichnofacies, respectively. In the L-D and L-Dw couplets, sedimentation rates and energy levels were very great in storm dominated settings for benthic organisms to colonize the substrate. Majority of the trace fossils are vertical to subvertical, and represent the domiciles of deeply burrowing suspension-feeding organisms. Consequently, the impoverishment of deposit-feeding and grazing structures all through proximal tempestites due to waning current velocities, increased depositional rates for material with lower settling velocities, and the reduced variation in food resources and the presence of substrates that mainly favor vertical dwelling traces is seen.

Ichnotaxon	Ethological grouping	Description	Environmental distribution	Environmental distribution in Deh-Sufiyan Formation
Arenicolites isp, (Fig. 7a)	Dwelling burrows of of suspension-feeding annelids.	Vertical U-tubes, circular in cross section, parallel to each other; found in the bedding plane; burrow diameter of tubes 2-6 mm.	Eurybathic trace fossil recorded in diverse environments.	Rare in facies association (FA3); Rare in L-De; Common in L-D, L-Dw
Bergaueria isp. (Fig. 8b, d)	Resting burrows of activities of a cerianthid or actinarian anemones.	Hypichnial mound in the lower surface of beds, oriented perpendicular to bedding; with hemispherical termination with rounded base; 5-8 mm long, and 5-8 mm high.	Eurybathic trace fossil	Rare in facies association (FA3) and L-De; Relatively common in L-D; Very rare in Gg-S or Gg-Lm; Very rare in L-M
Chondrites isp. (Fig. 9c)	Infaunal deposit-feeders, living at the aerobic/anoxic interface as chemo-symbiotic organism.	System of tree-like burrow, endichnial burrows with numerous downward penetrating branches of flattened tunnels; gently curved burrows; burrow diameters (1 to 2 mm).	Eurybathic trace fossil especially at low oxygen environments.	Relatively common in Shale/marl-dominated facies association (FA1); Very rare in L-M; Rare in L-S
Circuliuchnis isp.	Deposit-feeding structures	Epichnial burrows in the top surface of beds, small, rounded or flattened in outline; unornamented walls; oriented perpendicular to bedding; unlined, unbranched, lacking internal structures; outer diameter 30 mm and tube diameter 5 mm	Living in slightly turbulent nearshore water or shallow-marine environments	Very rare in Gg-S or Gg-Lm; Very rare in L-M
?Cruziana isp., (Fig. 8d, e)	Locomotion (pascichnion) of arthropod	Bilobate trace with broad well defined central furrow; convex hyporelief ribbon like traces; smooth winding or stright burrows; width varies from 10 to 30 mm, and remains constant along exposed length; length is often incomplete but is up to 10 cm.	Typical of the shallow marine *Cruziana* ichnofacies	Rare in L-M and L-S
Didymaulichnus isp. (Fig. 6f)	The crawling trail (pascichnia) of worm-like organism or mollusk moving obliquely through the sediment	Ribbon like traces, long, straight or curved burrows preserved in convex hyporelief; bilobate trails about 5 to 12 mm wide; lobes separated by distinct furrow; maximum observed length is 10 cm.	Typical of the shallow marine *Cruziana* ichnofacies	Rare in L-Dw; Relatively common in Gg-S or Gg-Lm; Very rare in L-M
Diplichnites isp.(Fig. 5d)	Crawling activity of an arthropod, mostly trilobites on the soft sediments.	Trackway consisting two parallel series of fine markings; parallel, paired; individual ridges; elongate and oblique to the track axis; preserved in convex hyporelief; distance between two rows up to 8 mm.	Eurybathic trace fossil; typical of the shallow marine *Cruziana* ichnofacies.	Rare in facies association (FA3) and L-De; Relatively common in L-D; Relatively common in Gg-S or Gg-Lm; Rare in L-M
D. gouldi (Fig. 6c)	Crawling activity of arthropods	Series of parallel ridges; oriented perpendicular to the track axis; elongate to ellipsoidal imprints; preserved in convex hyporelief; distance between two rows 5-10 mm.	Eurybathic trace fossil	Relatively rare in L-D
*Diplocraterion*isp. (Fig. 7a, dl)	Dwelling burrow (domichnia) of suspension-feeding organisms	Vertical, U-shaped burrow as a dumb-bell shaped trace; pair of circular openings on surface joined by spreite; the burrow tube is 5-20 mm apart, 5-10 mm in diameter.	Characteristic of settings with strong wave and current energy	Common in L-D and L-Dw; Relatively common in Gg-S or Gg-Lm
Fugichnion (Fig. 7c, I and 8j)	Escape structures in response to episodic sedimentation	Straight to slightly curve burrows slightly taper over their length of several centimeters, unlined with downwarping of strata in their central part; with 1 to 5cm in length.	Developed under high sedimentation conditions.	Rare to relatively common in L-D and L-Dw; Relatively rare in Gg-S or Gg-Lm
?Gyrophyllites isp. (Fig. 4b)	Feeding trace (fodinichnial) produced by worm-like organisms	Rosette epichnial traces; with a circular area encircled by radial feeding galleries or leaf-like tunnels; tunnels are irregular in shape due to low preservation; mostly club-shaped; diameter 50mm; 10-150mm elongated leaf-like tunnels tapering to a central point.	Typical of the deep marine *Zoophycos*and *Nereites* ichnofacies	Very rare in Shale/marl-dominated facies association (FA1)
Halopoa isp.(Fig. 6b)	Considered as back-filled, feeding burrows	Endichnial or hypichnial, cylindrical burrows, straight to slightly curved, horizontal; unbranched, unlined; burrow margins lined and ornamented by longitudinal parallel grooves; 50-100 mm length and 10 to 15 mm in diameter.	Eurybathic trace fossil recorded in diverse environments from shallow-marine to submarine fans	Relatively common in L-D
H. annulata (Fig. 6a)	Considered as back-filled, feeding burrows	Straight to slightly curved, horizontal, full relief hyporeliefs; unbranched, unlined, relatively long burrow; encircled by thin ring-like structures or distinctly placed annulations; 50-150 mm length and 10 to 20 mm in diameter.	Eurybathic trace fossil	Relatively common in L-D
Helminthopsis isp. (Fig. 8a)	Grazing trail (pascichnion) to locomotion trail (repichnion) of a worm-like organism	irregularly meandering, horizontal, cylindrical, unbranched burrows; thinly walled burrow; burrow diameter is constant throughout courses, maximum observed length is 7 cm.	Eurybathic trace fossil recorded in diverse environments.	Very rare in Shale/marl-dominated facies association (FA1); Rare in L-Dw; Rare in Gg-S or Gg-Lm; Very rare in L-M
H. abeli (Fig. 9d)	Grazing trails	The traces occur in concave hyporelief and as winding to irregularly meandering; cylindrical to sub-cylindrical burrows, with open meanders and horseshoe-like turns; 5 mm wide and 10 to 30 mm long.	Eurybathic trace fossil	Very rare in L-M
Gordia isp. (Fig. 7f and 9e)	Grazing trail (pascichnion) to locomotion trail (repichnion) of a worm-like organism	Irregularly looping, long, winding to irregularly meandering worm-like trails; irregular courses with over-cross; with variable lengths; trails are 2 mm to 5 mm in diameter; maximum observed length is 10 cm.	*Gordia* is a facies-crossing form that occurs in both marine and non-marine settings.	Rare in Gg-S or Gg-Lm; Very rare in L-M and L-S
Lockeia cf *siliquaria* (Fig. 6g)	Resting traces of bivalves	Convex, hypichnial, almond-shaped traces, bilaterally symmetrical; tapering at both ends (blunt); with central median ridge or crest; 10 to 15 mm length, 5-10 mm width and 4-8 mm height.	Eurybathic trace fossil recorded in marine and non-marine environments	Relatively common in L-D; Rare in L-Dw; Very rare in Gg-S or Gg-Lm; Rare in L-M;
Monocraterion isp. (Fig. 6h)	Opportunistic and facies-crossing trace with a suspension-feeding and domichnia function.	Vertical, straight, simple, cylindrical structures; conical concentric around a central shaft; with mud lining along burrow wall of both tubes and funnels; found in the bedding plane; 10 to 15 mm.	Mainly energetic marine environments.	Rare in L-Dw
Monomorphichnus isp. (Fig. 6c and 8c)	walking arthropods, mostly trilobites; by the sideways propagation of the animal	Sets of imprints arranged in a row; isolated, slightly curved imprints repeated laterally; imprints 5–18 mm length, 1–2 mm width and 2–3 mm apart from each other.	Recorded in shallow-marine, brackish and continental environments; typical of the shallow marine *Cruziana* ichnofacies.	Relatively common in L-D; Very rare to rare in L-M
Palaeophycus isp. (Fig. 5c)	Open dwelling burrow of a suspension feeder or predator, either worm-like organisms	Horizontal to slightly inclined, slightly curved, unbranched, endichnial, cylindrical burrows; lined, smooth-walled; 10-15 mm in diameter and 50-100mm length.	Eurybathic trace fossil, deposited in a broad range of marine environments.	Rare in facies association (FA3) and L-De; Common in L-D; Common in L-Dw; Relatively common in Gg-S or Gg-Lm; Very rare in Gg-S

Ichnotaxon	Ethological grouping	Description	Environmental distribution	Environmental distribution in Deh-Sufiyan Formation
P. tubularis, (Fig. 5i)		Endichnial or hypichnial, straight to slightly curved cylindrical to subcylindrical burrows; unornamented, unbranched, with discrete lining; burrow fill is structureless and identical to the host rock; 10-15 mm in diameter and 30-100mm length..	Eurybathic trace fossil, deposited in a broad range of marine environments.	Relatively rare in L-D
Phycosiphon isp. (Fig. 4d)	Opportunistic deposit feeder	Narrow and sinuous U-shaped tubes, irregularly twist; as a series of lobes as protrusive spreiten-structures; with various orientations of the lobes; without preservation of spreiten between arms	Deposited in a broad range of marine environments from shallow-marine to submarine fans.	Very rare in Shale/marl-dominated facies association (FA1)
Planolites isp. (Fig. 4d, 4c, 8d)	Polyphyletic vermiform deposit-feeders (pascichnion) producing active backfilling	Straight to slightly curved burrows with smooth walls, unlined, unbranched burrow, horizontal to slightly inclined; hyporelief; with a structureless infill that is compositionally different from the sedimentary matrix of the host rock; 15 to 40 mm length and 8 to 15 cm diameter	Regarded as a eurybathic, extremely facies-crossing form.	Relatively common in Shale/marl-dominated facies association (FA1); Rare in facies association (FA3); Common in L-D; Very rare in Gg-S or Gg-Lm; Very rare in L-M and L-S
P. beverleyensis (Fig. 4f)	The backfilled burrow of a worm-like mobile deposit feeder	Endichnial, hypichnial; cylindrical, unbranched, unlined, long burrow, cylindrical, smooth walled, straight to gently curved, 5–10 mm in diameter, length of the burrow varies from 40 to 100 mm.	Eurybathic trace fossil.	Common in L-D; Very rare in Gg-S or Gg-Lm
P. montanus (Fig. 8g)	The backfilled burrow produced by a non-selective, endobiont detritus feeder	Hypichnial, subcylindrical to cylindrical, small vermiform structures with smooth walls, unlined, unbranched; undulose, tortuous, showing rectilinear to slightly curved burrows of flattened to cylindrical section; burrow width is 1 to 5 mm.	Regarded as a eurybathic, extremely facies-crossing form	Very rare in L-M and L-S
Rosselia isp.(Fig. 7b)	Dwelling burrows (domichnia) of filter feeding organisms, or polychaete annelids.	Vertical or subvertical burrows slightly taper over their length of several centimeters; conical or funnel-shaped burrows with concentrically lined cylinders with distinct mud lining; found in the bedding plane, epichnial; with 5cm in length and 5 to 18 mm in across;	Living in slightly turbulent nearshore water or shallow-marine environments with sufficient bottom water circulation.	Relatively common in L-D; Rare in L-Dw; Relatively rare in Gg-S or Gg-Lm; Very rare in L-M
R. socialis (Fig. 5h)	Dwelling structure of detritus feeding organisms and polychaetes.	The endichnial and epichnial preservations; vertical or subvertical burrows; conical to funnel-shaped structures consisting with concentric infill around a cylindrical shaft; 2 to 3cm in length and 5 to 15 mm wide.	Common in shallow-marine environments, developed under normal salinity or brackish conditions	Relatively common in L-D
Rusophycus carbonarius (Fig. 6e)	Resting trace of tiny arthropod	Bilobate traces, rounded convex hypichnia; coffee-bean-shaped; subcircular with two parallel lobes separated by a central groove; lobes are parallel, rarely oblique; covered by fine transverse striae with low preservation; with gape at the anterior end and steep posterior part; 10-20 mm in length and 5 to 15 mm in across.	Typical of the shallow marine *Cruziana* ichnofacies	Rare in L-Dw; Relatively rare in Gg-S or Gg-Lm; Very rare to rare in L-M and L-S
R. didymus (Fig. 8a)	Resting trace of tiny arthropod	Bilobate traces, bilaterally symmetrical, hypichnial; with a median furrow, wider and shallower towards the anterior end; commonly gaping towards the anterior end; the lobes separated by a v-shaped median furrow; lobes smooth: 10-20 mm in length and 5 to 10 mm in across.	Typical of the shallow marine *Cruziana* ichnofacies	Rare in L-M
R. eutendorfensis (Fig. 7j)	Trilobite resting (cubichnion) excavation	Hypichnial, bilobate traces, symmetric mounds; coffee-bean-shaped; with two parallel lobes separated by a central groove; without transverse scratch marks on lobes, mostly smooth lobes; with 10-20 mm in length and 5 to 15 mm in across.	Typical of the shallow marine *Cruziana* ichnofacies	Rare in L-M
Skolithos isp., (Fig. 5h and 7a, c)	Domichnion structure by phoroids or annelids and suspension feeding polychaetes.	Vertical, straight, simple, found in the bedding plane; isolated burrows; ranging from 5 to 10 mm in width.	generally associated with high-energy, nearshore marine sands and typical of the shallow marine *Skolithos* ichnofacies	Rare in facies association (FA3) and L-De; Common in L-D and L-Dw; Relatively common in Gg-S or Gg-Lm
Treptichnus pedum (Fig. 7j and 8h)	Fodinichnion made by vermiform animals	Hypichnial traces consisting of individual elongate to ellipsoidal, straight to slightly curved smooth segments; irregular branching patterns with straight to irregularly meandering course; segments 5 to 10 mm in length and 2 to 3 mm inwidth;	Typical of the shallow marine *Cruziana* ichnofacies	Very rare in L-M

Taking into consideration the stated characteristics, at the peritidal settings in the L-De couplets and FA3, land processes affected (includes temperature fluctuations, discharging groundwater, and episodes of desiccation) the marine realm resulting in a variety of environmental stresses on the infaunal organisms. The trace fossil suite in the peritidal settings is indicative of a stressed expression of the mixed *Skolithos-Cruziana* ichnofacies and stressed *Skolithos* ichnofacies (MacEachern et al. 2007b). Physico-chemical stresses are largely the cause of river-induced processes and increased fluctuations in salinity (MacEachern et al. 2005; Bayet-Goll and Neto de Carvalho 2015). The nature of the resident ichnofaunas in brackish-water environments is greatly affected by salinity (MacEachern et al. 2007b). Peritidal settings of the Unit 2 of the Deh-Sufiyan Formation, which is typically formed in restricted brackish-water settings, is likely to contain low-diversity ichnofauna dominated by intermittent distributions of burrowing, smaller size of ichofaunas and simple feeding strategies of facies-crossing ichnogenera. Consequently, peritidal settings of the Unit 2 are characterized by "stressed" ichnological assemblages. The interaction of coastal processes resulted in a variety of physico-chemical stresses imposed on infaunal organisms, and this is reflected in the "stressed" trace fossil assemblages of most peritidal successions. The "Stressed" ichnological suites are characterized by impoverished trace fossil assemblage diversities, significant reductions in bioturbation intensity, sporadic distribution of ichnofossils all through the deposits, smaller size of ichofaunas,and horizontal, simple feeding strategies (MacEachern et al. 2007a, b; Bhattacharya et al. 2011; Bayet-Goll and Neto de Carvalho 2015).

7. Conclusion

Trace fossil assemblages are identified as a crucial element contributing to the characterization of the depositional facies in the Unit 2 of the Deh-Sufiyan Formation. The succession accumulated on a gently dipping shelf dominated by storm and fair weather wave processes and comprises deep subtidal, shallow subtidal, lower intertidal, upper intertidal, and supratidal environments. The ichnological, sedimentological and stratigraphic framework of the Deh-Sufiyan Formation have been employed to produce a facies model that may be used to enhance facies characterization and to enhance palaeoenvironmental interpretation of the carbonate succession in a wave-dominated carbonate ramp. Twenty-one ichnogenera have been identified in the Deh-Sufiyan Formation. The distribution of trace fossil, composition of ichnological assemblages, ichnodiversity, and ethological grouping of the trace fossils is strongly connected with inferred degree of stability and temporal persistence of physico-chemical conditions. The ethological grouping of the trace fossils as a reslt of physico-chemical depositional stresses defines the proximal-distal ichnofacies gradients pattern of wave-dominated coastal successions of the Deh-Sufiyan ramp. Proximal and distal facies of onshore-offshore successions of this study indicate departures from the archetypal ichnofacies and distinct reductions in the bioturbation intensity, intermittent distribution of burrowed intervals, and impoverished assemblage diversities. Considering the obvious deepening of the shallow marine depositional systems of the wave-dominated parts of the carbonate ramp, the succession of archetypal ichnofacies can express a bathymetric trend from deeper to shallower parts, and from lower-to-higher hydrodynamic condition for the shallow marine depositional systems of the Unit 2 of the Deh-Sufiyan Formation.

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