Significance of ichnofossils in high resolution sequence stratigraphy: Upper Maastrichtian, Kopeh- Dagh Basin, NE Iran

Amir Karimian Torghabeh[1], Asadollah Mahboubi [1], Reza Moussavi-Harami[1]* , Moyra E.J.Wilson[2]
[1]*Department of Geology, Faculty of Science, Ferdowsi University of Mashhad, Iran*
[2]*Applied Geology Department, Curtin University of Technology, Perth, Western Australia*
**Corresponding author, e-mail: harami2004@yahoo.com*
(*received: 10/02/2012 ; accepted: 28/05/2012*)

Abstract

This study shows that ichonology can be used to refine sequence stratigraphy as well as to interpret the depositional environment of the Kalat Formation (Upper Maastrichtian) in the Central Kopeh- Dagh Basin (NE Iran), Dareh-Gaz section. Field studies and petrography of these deposits led to recognize four lithofacies and nine subfacies that formed in the tidal flat (lithofacies A), lagoon (lithofacies B), shoal (lithofacies C), and open marine (lithofacies D) within a carbonate ramp system. Trace fossils in this succession consist of *Psilonichnus quietis*, *Thalassinoides suevicus*, *Diplocraterion parallelum*, *Rhizocorallium jenense and Ophiomorpha* isp. that are classified in the *Psilonichnus ichnofacies* and *Thalassinoides suevicus*, *Diplocraterion parallelum*, *Rhizocorallium jenense,* and *Ophiomorpha* isp. in the *Cruziana ichnofacies*. Based on lithofacies and ichnofacies analyses, two depositional sequences (DS_1 and DS_2) were identified, that are composed of transgressive and highstand systems tracts. The maximum flooding surface (MFS) in DS_1 is characterized at the top of the bed containing *Rhizocorallium jenense*, while this surface in DS_2 is recognized by *Diplocraterion parallelum* grading into *Ophiomorpha* isp. in similar lithofacies. This study is an example where ichnology provides additional support for high-resolution sequence stratigraphy in carbonate deposits. Moreover, our study demonstrates that trace fossils could be useful in identification of the MFS in similar lithofacies elsewhere.

Key Words: *Ichnofacies, Maastrichtian, System tract, Kalat Formation, NE Iran*

Introduction

The main applications of ichnology in sequence stratigraphic analysis are (1) the enhancement of environmental interpretations; and (2) the identification of key surfaces and erosional discontinuities particularly where there is a significant temporal break between the eroding event and the deposited strata (Savrda, 1991; Pemberton and MacEachern, 1995; Pemberton *et al*., 2001, 2004; Rodriguez-Tovar *et al*., 2007). Integration of ichnological analysis with sedimentological data can also be used to determine facies and sequence variations depend upon water depth and energy conditions (Pemberton and MacEachern, 1995). In the eastern Kopeh-Dagh Basin, sequence stratigraphic analysis of the Upper Maastrichtian Kalat Formation was carried out by characterizing the lithofacies (Mahboubi *et al*., 2006). However, identifying sequence stratigraphic trends within the central part of the basin was more difficult due to poor facies expression and scarcity of well-differentiated key boundary surfaces. Here, we combine ichnological and lithofacies studies (based on field observations and the examination of 100 thin-sections) to infer depositional environments, changing environmental conditions, and sequence development within the Kalat Formation in northeast Iran in the central Kopeh-Dagh Basin in the Darh-Gaz region, southeast of the Greater Caspian Region (Fig. 1).

Geological setting

The Kopeh-Dagh Basin was formed after the Middle Triassic orogeny as a result of the closure of the Hercynian Ocean in northeast Iran (Berberian and King, 1981; Şengor, 1987; Şengor *et al*., 1988; Ruttner, 1993; Alavi *et al*., 1997; Golonka, 2004). In this basin, sedimentation was nearly continuous from Jurassic through the Neogene (Afshar-Harb, 1969, 1979, 1994; Kalantary, 1987). Five major transgressive and regressive sequences have been identified in the eastern part of the Kopeh- Dagh Basin (Moussavi-Harami and Brenner, 1992). Shallow marine to shoreline sediments of the Early Maastrichtian Neyzar Formation were deposited during relative sea level fall (Moussavi-Harami & Brenner, 1992), while during the Late Maastrichtian, relative sea level rose again and the Kopeh-Dagh Basin became a region of shallow marine environments (Smith *et al*., 1994; Mahboubi *et al*., 2006). At this time, the carbonates of the Kalat Formation were deposited in shoreline to inner ramp settings (Mahboubi *et al*., 2006). In the Early Paleocene time, the redbed

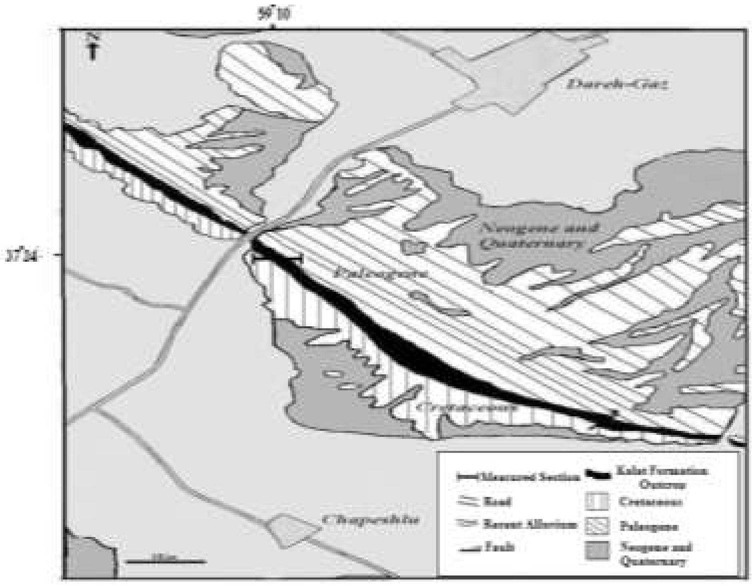

Figure 1: Location and summarized geologic map of the study area (Modified from Afshar-Harb, 1982).

sediments of the Pesteligh Formation were deposited during complete regression of the sea from the Kopeh-Dagh Basin towards the northwest (Moussavi-Harami, 1993). In the central part of the basin, the Kalat Formation was deposited in a shallow marine carbonate ramp with diagnostic ichnofossils. This formation conformably overlies calcareous sandstones of the Neyzar Formation, and, following a period of erosion, is unconformably overlain by red conglomerates and sandstones of the Pestehleigh Formation (Fig. 2).

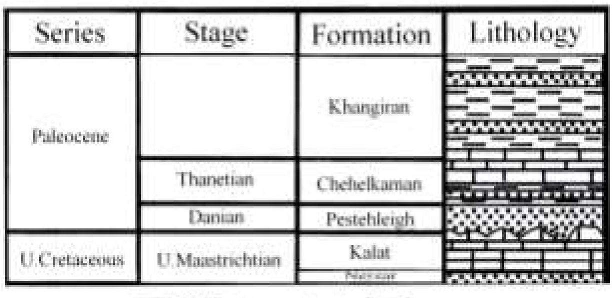

Figure 2: Simplified stratigraphic column of the Kalat Formation, central and eastern Kopeh-Dagh Basin (modified from Moussavi Harami & Brenner, 1992).

Lithofacies and trace fossils analyses

A combination of lithofacies and ichnofacies analyses is useful for interpreting depth and energy condition during deposition of different lithofacies associations (Pemberton & MacEachern, 1995). Detail of facies analysis including lithologic features, sedimentary structures and trace fossil content, led to the identification of four (A-D) lithofacies associations (Table 1, Fig. 3).

Lithofacies association A

This lithofacies consists of three subfacies: (A_1) Sandy intraclastic packstone-grainstone (Fig. 4A), (A_2) sandy intraclastic and bioclastic packstone-grainstone (Fig. 4B), and (A_3) Sandy bioclastic packstone-grainstone (Fig. 4C). These lithofacies are composed of fine-grained quartz sand (15-20%; 0.6 mm), bivalve debris (5-10%; 0.4 mm), benthic foraminifera (5-20%; 0.2-0.5 mm), echinoderms (5-15%; 0.3 mm) and intraclasts (5-25%; 0.4 mm). Benthic foraminifera consist of *Siderolites* and *Rotalia*. Intraclasts are composed of bioclasts debris (bivalve dominated) associated with micritic matrix. Calcite cement in different shapes and some mud matrix is present in these lithofacies. Trough-cross beds of medium thickness dominate in this lithofacies and the bioturbation index is low.

Trace fossils.- Psilonichnus quietis occurs most commonly as unlined, vertical, Y-shaped and cylindrical tubes. At the studied location (Fig. 6A), these traces have near-vertical main shaft, swelling and bedding-orientation that document a gravity-equilibration style of behavior, and characteristic features include average tube diameter about 15 mm and maximum burrow length of 60 to 80 mm that present in sandy intraclastic packstone-grainstone lithofacies (A_1). *Psilonichnus quietis* is

Table 1: Description of lithofacies and ichnofossils recorded in the sections studied.

Lithofacies	Description	Ichnofossils	Interpretation
A	Sandy intraclastic packstone-grainstone Sandy intraclastic bioclastic packstone-grainstone Sandy bioclastic packstone-grainstone	Psilonichnus quietis	The cross-bedded strata, grain-supported texture and siliciclastic influx with Psilonichnus characterize high energy tidal flat environment
B	Peloidal intraclastic packstone Peloidal benthic foraminiferal packstone-grainstone	Thalassinoides suevicus	Peloid and mud-supported fabric with low energy trace fossils determine low energy as Lagoon environment
C	Sandy peloidal intraclastic grainstone Bioclastic intraclastic grainstone Bioclastic grainstone	Diplocraterion paralleleum.	Grain-supported texture and subangular quartz grains and intraclasts indicate a high-energy shoal environment
D	Peloidal red algal packstone	Rhizocorallium jenense Ophiomorpha isp Diplocraterion parallelum	The micritic matrix, red algal and spicules sponge indicate low-energy open shelf

diagnostic trace fossils in studied section. Evaluation of occurrence of *Psilonichnus* in its biological, ecological and physical context is necessary for accurate paleoenvironmental identification (Nesbitt and Campbell, 2006). *Psilonichnus quietis* was originally described from shallow marine sediments of the Eocene Joban Coal Field in Japan (Myint, 2001), where this ichnospecies occurs in strata which is gradually shifting from a terrestrial setting to transgressive conditions. *Psilonichnus* can be found in different ichnofacies including: (1) *Glossifungites ichnofacies* of intertidal to supratidal flats/banks sediments (Gingras *et al*., 1998, 2002; Nesbitt and Campbell, 2006; Pemberton and Frey, 1985) which is mainly controlled by substrate, (2) *Psilonichnus ichnofacies*, which characterizes backshore to coastal-dune areas (Nesbitt and Campbell, 2006; Pemberton *et al*., 1992b), and (3) *Skolithos ichnofacies* that occurs within sediments of the outer-estuarine and bay-mouth setting (Campbell and Nesbitt, 2000; Nesbitt and Campbell, 2002).

Interpretation- The cross-bedded strata, grain supported texture and siliciclastic influx characterize high-energy environments (e.g., Nader *et al*., 2006; Olivier *et al*., 2008). *Psilonichnus quietis* have been found in tidal flat sediments, which consist of shifting substrate to high energy conditions during transgression (Fürsich, 1981; Pemberton and MacEachern, 1995; Myint, 2001; Nesbitt & Campbell, 2006). Presence of *Psilonichnus* in A_1 could be assigned to formation of this subfacies closed to marine condition in contrast to other subfacies in the lithofacies A.

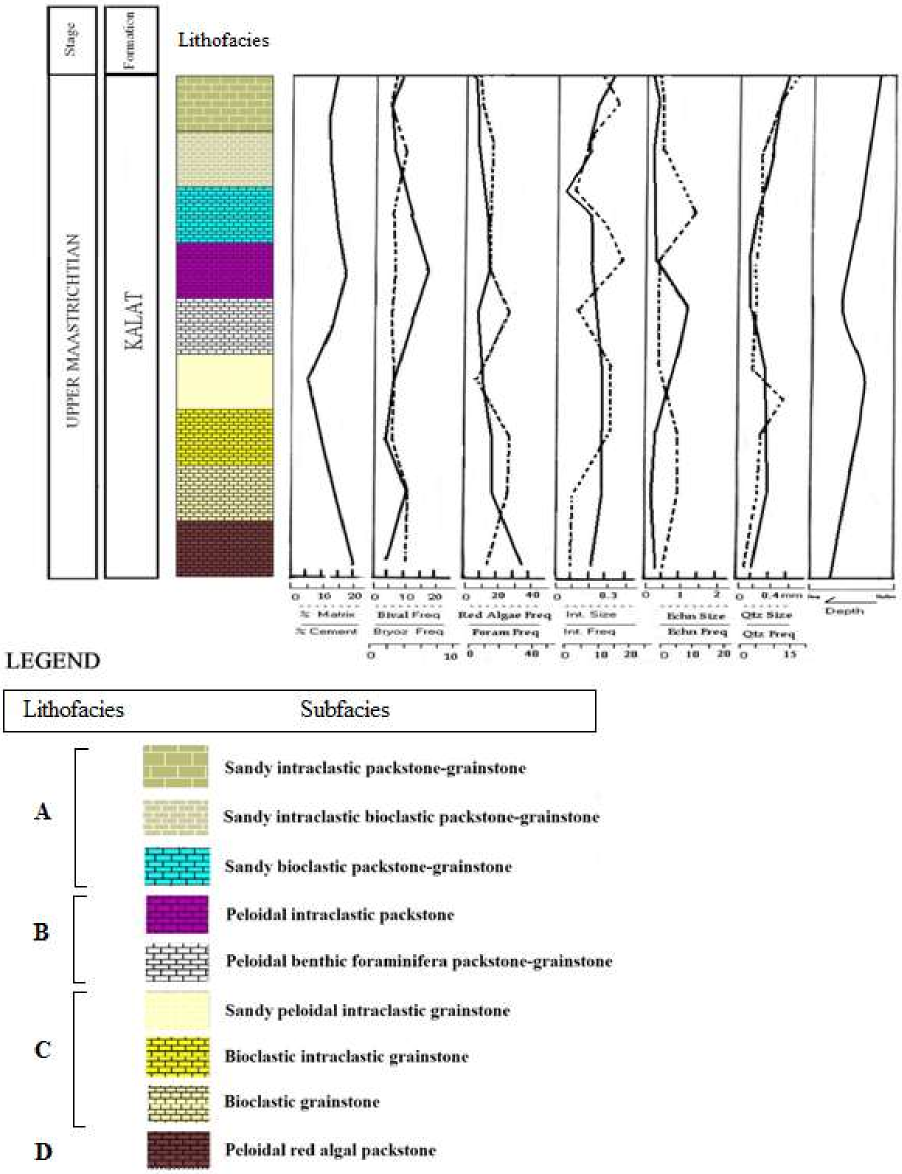

Figure 3: Idealized shallowing-upward sequence with lithofacies properties that show complete lithofacies associations in unique shallowing stage. (Abbreviaations: Bival=Bivalve, Bryoz=Bryozoa, Foram=Foraminifera, Ech=Echinoides, Qtz=Quartz, In=Intraclast, Freq=Frequency).

Lithofacies association B

Two subfacies were identified in this association: (B_1) Peloidal intraclastic packstone (Fig. 4D) and (B_2) Peloidal benthic foraminiferal packstone-grainstone (Fig. 4E). This association consists of peloids (10%; 0.1 mm in diameter), benthic foraminifera (10-20%; 1.5 mm) and intraclasts (5-25%; 0.3 mm) and has a higher matrix/cement ratio than lithofacies A. *Orbitoides, Lepidorbitoides, Siderolites, Miliolide* and *Rotalia* are dominant foraminifera in this association. Bioclastic debris (bivalve shell) with micritic matrix is components in intraclasts. Bioturbation index is medium.

Trace fossils.- Two trace fossils were found in lithofacies B. *Thalassinoides suevicus* occurs as isolated and Y-shaped branching cylindrical burrows (e.g., Pemberton and MacEachern, 1995; Fig. 6B). The average diameter of the tubes is 2 cm and the maximum observed burrow length ranges from 10 to 30 cm. This trace fossil is a typical component of three ichnofacies: the *Glossifungites, Teredolites* or *Cruziana* (Pemberton and MacEachern, 1995; and Seilacher, 2007). *Ophiomorpha* isp. Is another traces that consists of irregularly inclined cylindrical burrows with a pelleted wall structure (Fig. 6C). The diameter of the cylindrical tubes is approximately 1 cm and maximum burrowing depth is 10 cm. Both of trace fossils present in peloidal intraclastic packstone (B_1).

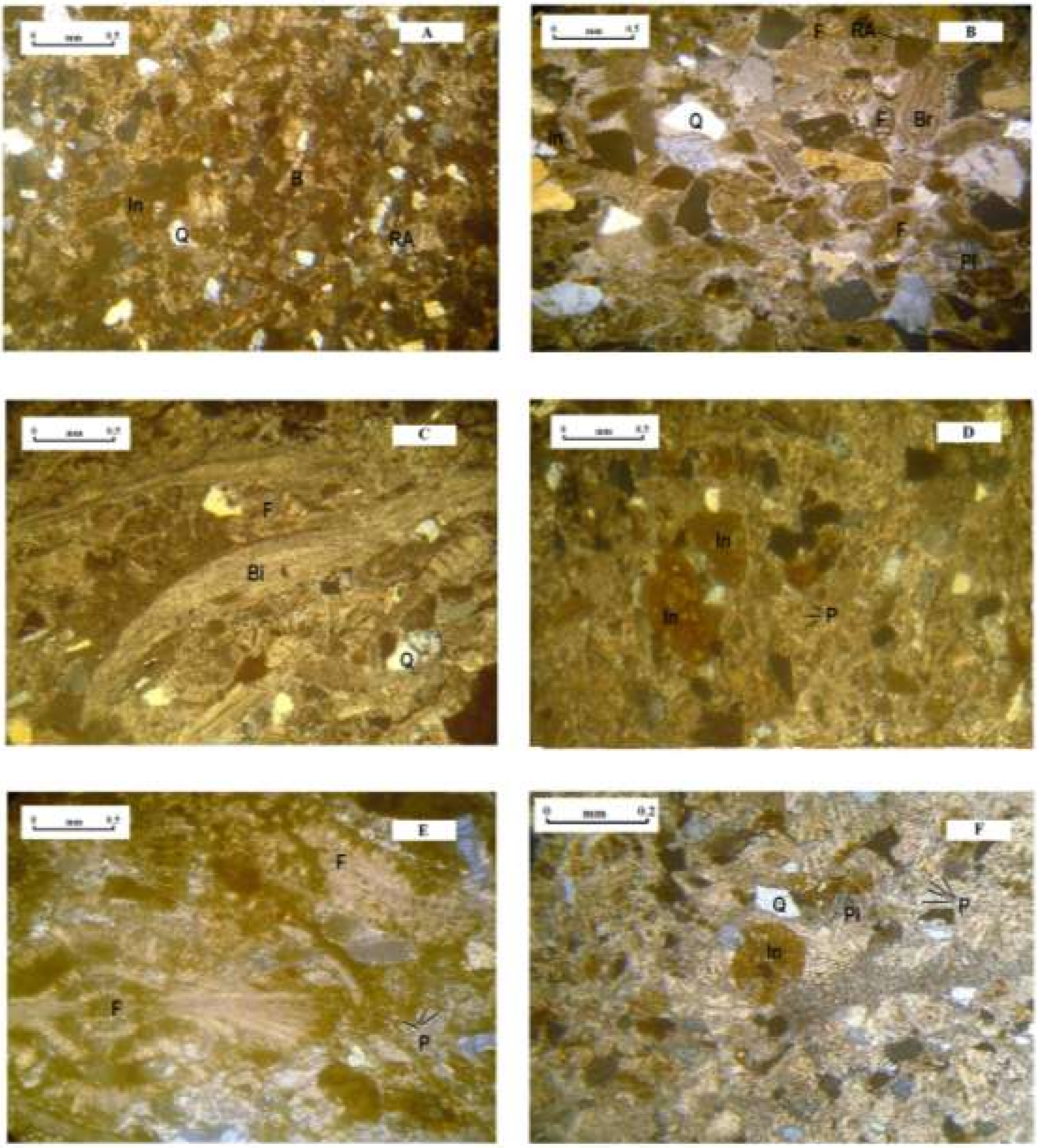

Figure 4: Microscopic images from lithofacies (XPL), A) Sandy intraclastic packstone-grainstone; B) Sandy intraclastic bioclastic packstone-grainstone; C) Sandy bioclastic packstone-grainstone; D) Peloidal intraclastic packstone; E) Peloidal bentic foraminifera packstone-grainstone ; F) Sandy peloidal intraclastic grainstone (Q- quartz, Br- bryozoans, Pl- plagioclase, In- intraclast, P- peloid, F- foraminifera , RA- red algal, Bi- bivalve, P- peloid).

Interpretation.- Presence of peloids (e.g., Cadjenovic *et al*., 2008), large benthic foraminifera (e.g., Flügel, 2004) and mud-supported fabric (e.g., Wilson, 1975) indicate deposition within shallow low-energy environmental condition (e.g., lagoon). *Thalassinoides* (Malpas *et al*., 2005; Wanke & Wanke, 2007) and *Ophiomorpha* isp. (Monaco *et al*., 2007) also can form under low energy environmental conditions, which supports this interpretation. Presence of both trace fossils in B_1 subfacies show that B_1 formed in deeper water with respect to B_2. The presence of both *Ophiomorpha* and *Thalassinoides* in lower part and only *Ophiomorpha* in the middle part within subfacies B_1 (Fig 7), show that the lower part was deposited in deeper condition than middle part of succession.

Lithofacies association C

This lithofacies consists of three subfacies: (C_1) Sandy, peloidal and intraclastic grainstone (Fig. 4F); (C_2) Bioclastic and intraclastic grainstone (Fig. 5A), and (C_3) Bioclastic grainstone (Fig. 5B). Intraclasts (5-15%; 0.4 mm in diameter), peloids (2-10%; 0.1 mm), benthic foraminifera (10-25%; 0.2-1.6 mm), and detrital quartz grains (5-20%; 0.4 mm) are dominant particles. *Siderolites* are the dominant large benthic foraminifera. Intraclasts contain bioclastic debris in a micritic matrix. The ratio of calcite cement to matrix is relatively high in this lithofacies. Bioturbation index is medium.

Trace fossils.- Diplocraterion parallelum is a vertical U-shaped burrow with spreiten (e.g., Pemberton & MacEachern, 1995; Fig. 6D). The size is variable, but the average horizontal distance between the corresponding vertical shafts is 25-35 mm. The burrow diameter is between 2 and 3 mm and the maximum burrow depth is between 40-55 mm. This trace fossil present in subfacies C_2 and C_3.

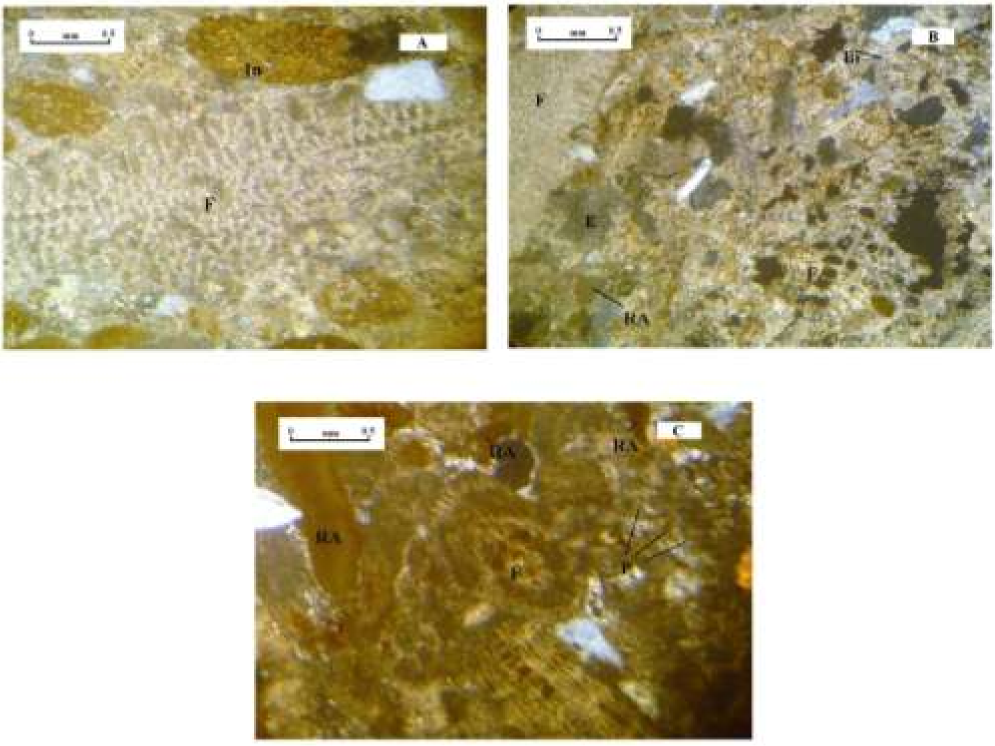

Figure 5: Microscopic images from lithofacies (XPL), A) Bioclastic intraclastic grainstone (In- intraclast, F- foraminifer); B) Bioclastic grainstone (Bi- bivalve, F- foraminifera, E- echinoderm, RA- red algal); C) Peloidal red algal packstone (RA- red algal, P- peloid, F- foraminifera).

Interpretation.- Grain-supported texture (e.g., Masse *et al*., 2003), subangular quartz grains (e.g., Coffey & Read, 2004) and subangular intraclasts (e.g., Cadjenovic *et al*., 2008) indicate a high energy environment such as bar which was affected by wave action. *Diplocraterion parallelum* is characteristic of high-energy unstable environments (Fürsich, 1974; Oloriz & Rodriguez-Tovar, 2000). This trace fossil is interpreted as the dwelling structure of a filter-feeder animal (e.g., Cornish, 1986) and occurs in the *Glossifungites, Skolithos* and *Cruziana ichnofacies* (Pemberton *et al*., 2001; Seilacher, 2007). Presence of this trace fossil in subfacies C_1 and C_2 may show deeper condition for deposition of these subfacies than subfcaies C_1.

Lithofacies D

This lithofacies consists of peloidal red algal packstone (Fig. 5C). Red algal remains (35%; 0.3mm in diameter), peloids (15%; 0.1 mm) and sponge spicules (2%; 0.2 mm) are dominant particles in this lithofacies. *Siderolites, Orbitoides* and *Rotalia* are dominant foraminifera. The micritic matrix cement ratio is high. Bioturbation index is high.

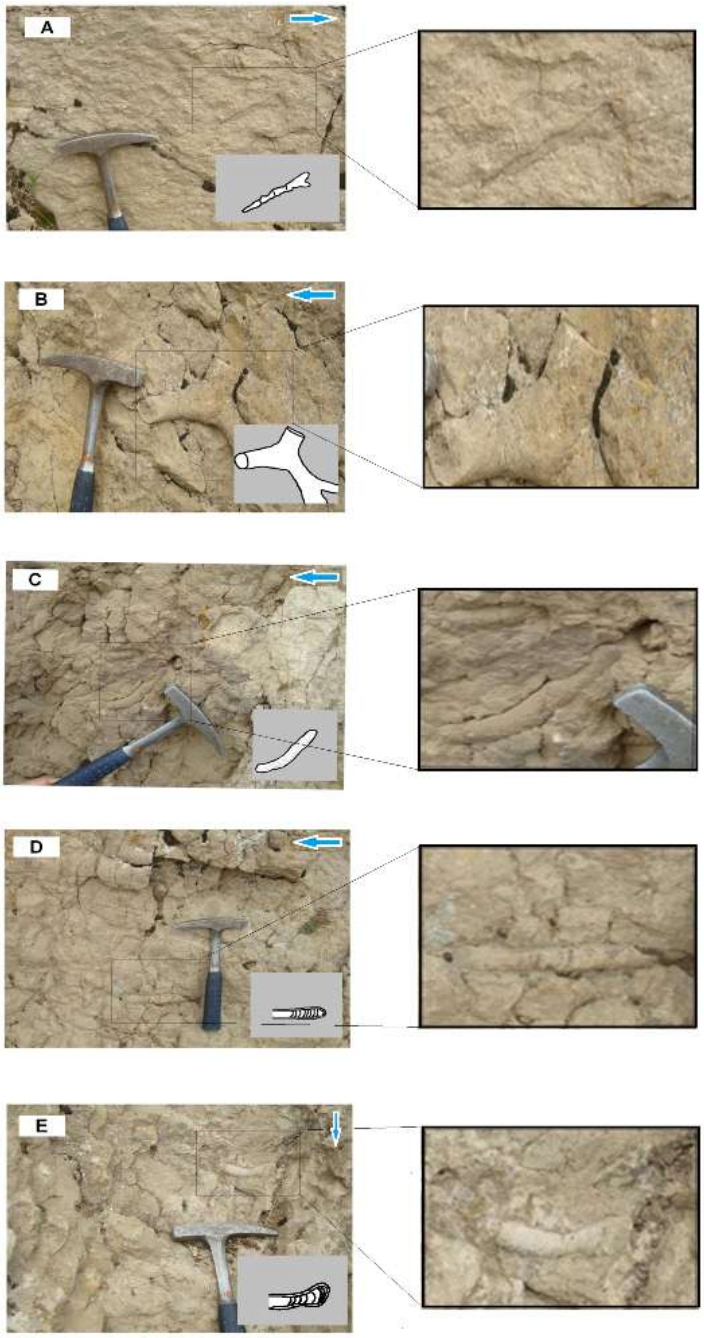

Figure 6: Trace fossils from the study area (arrow shows top of the bed): (A) *Psilonichnus quietis* (vertical), (B) *Thalassinoides suevicus* (vertical), (C) *Ophiomorpha* isp. (oblique), (D) *Diplocraterion parallelum* (vertical), (E) *Rhizocorallium jenense* (oblique).

Trace fossils.- *Rhizocorallium jenense* consists of short straight to slightly sinuous horizontal U-shaped spreiten burrow with distinct scratch mark (Fig. 6E). Tube diameter is 3 mm and the width of the spreiten burrow is 20-25 mm. Maximum observed length of the burrow is 75 mm. *Ophiomorpha* isp. and *Diplocraterion parallelum* are also present in this lithofacies.

Interpretation.- The presence of micrite (e.g., Adachi *et al*., 2004), red algae (Thomas *et al*., 2008) and sponge spicules (Flügel, 2004) suggest a low energy open marine environment. Also, *Rhizocorallium jenense* is a characteristic trace fossil of soft substrate *Cruziana* and firm substrate *Glossifungites ichnofacies* (Pemberton *et al*., 1992b). *Rhizocorallium* could be formed in low-energy regimes (R. irregulare; Fürsich, 1974, 1981) with soft substrate or in high-energy regimes

(Fürsich, 1981; Worsley & Mørk, 2001) with soft or firm substrates. *Ophiomorpha* isp. is also recorded from low-energy environments (Monaco *et al*., 2007) and occurrences of *Diplocraterion parallelum* depend upon numerous factors such as unconsolidated substrate, preservation potential and different energy conditions (Fürsich, 1975). In lower part of the succession, only *Rhizocorallium* present in lithofacies D and in the upper part, *Diplocraterion* with *Ophiomorpha* present and in the uppermost part, *Ophiomorpha* present in lithofacies D, therefore, the lower part can be deposited in deeper water.

Environmental interpretation

Based on lithofacies analysis, the Kalat Formation in the eastern Kopeh-Dagh Basin was interpreted to be deposited in a shallow marine carbonate ramp (Mahboubi *et al*., 2006). However, lithofacies in the central part of the basin are different from the eastern parts, where trace fossils and ichnofacies were studied for the first time. Lithofacies A and B were deposited in the shallowest parts of a carbonate ramp (under tidal flat and lagoonal conditions). Lithofacies C is a grain-supported and contains coarse bioclasts that was deposited in high-energy environmental conditions. Lithofacies D with abundant algal particles was deposited in a low-energy open-marine environment.

The four identified lithofacies show a characteristic ichnofaunas that are distributed with respect to depth and energy conditions. Lithofacies A is characterized by Psilonichnus and shifting substrate, that was formed in tidal flats and similar transitional environments, while lithofacies B with *Thalassinoides suevicus* and *Ophiomorpha* isp. is indicative of lagoonal and low-energy environments. Lithofacies C consists of *Diplocraterion* (high energy) that is probably related to shifting sediment type on bar forms, whereas lithofacies D contains *Rhizocorallium jenence* and near bar forms *Ophiomorpha* and *Diplocraterion*. *Psilonichnus*, reported from marginal marine environment (*Psilonichnus ichnofacies*, Pemberton *et al*., 2001). In the studied section, *Thalassinoides suevicus* (common), *Ophiomorpha* isp. (abundant), *Diplocraterion parallelum* (rare) and *Rhizocorallium jenense* (rare) were probably formed on the inner shelf (e.g., Pemberton *et al*., 2001) in a shallow *Cruziana ichnofacies* (e.g., Obon-Ikuenobe *et al*., 2005).

Ichnological approach and sequence stratigraphic interpretation

The two potential fold applications of ichnology to sequence stratigraphy are ground soft-related ichnofacies and other substrate-controlled ichnofacies (Pemberton & MacEachern, 1995; Catuneanu, 2006). Ground soft-related ichnofacies can be used for interpretation of paleodepositional environments and changes of depth and energy conditions through time. Therefore, regression and transgression of paleo-shorelines can be determined with ichnofossil approach. Other substrate-controlled ichnofacies can be used for the identification of unconformities in the rock record and thus has important application in sequence stratigraphy (Catuneanu, 2006). The ichnological approach was used here to characterize soft ground-related ichnofacies as well as interpretation of system tracts and sequence boundaries similar to what have been used in Triassic successions of southern Spain where ichnoloical approach used for determining *Glossifungites* ichnofacies as start of transgressive stage (Rodriguez-Tavor *et al*., 2007).

In the past, sequence stratigraphic analyses of the Upper Maastrichtian successions in the eastern Kopeh- Dagh were mainly done on the basis of sedimentological data, while in this study a combination of sedimentological and ichnological data have been used for sequence stratigraphic analysis in the central parts of the basin. Based on trace fossils, different lithofacies were used to identify the system tracts and maximum flooding surfaces, as they are thought to reflect variations in depth and energy conditions. Two depositional sequences (DS_1 and DS_2) were identified. Lithofacies A (tidal flat) in lower part of strata is divided into A_1 and A_2. Lithofacies A_1 occurs in the basal Kalat Formation and is represented by sandy limestone without any trace fossils. It follows the high stand system tracts (HST) stage, interpreted as a shelf margin wedge (SMW) (e.g., Robaszynski *et al*., 1994; Zagrarni *et al*., 2008). Continuous with lithofacies A_2, it has cross bedding and toward the top consists of the *Psilonichnus* ichnofacies (transition substrate) that shows further seaward at the base of transgressive system tracts (TST). At this stage, lithofacies A_2 changes to lagoonal lithofacies B with *Ophiomorpha* isp. in proximal and *Thalassinoides* in distal lagoon facies. This lithofacies also changes gradually to lithofacies C (shoal) and D (deep marine), which are characterized by *Diplocraterion parallelum* (high energy) and *Rhizocorallium jenense* (low energy), respectively. Therefore these variations indicate that *Psilonichnus ichnofacies* gradually changed into the *Cruziana ichnofacies*. Lithofacies D with red algal packstone and the associated *Rhizocorallium* is interpreted as deeper facies and its top surface in Ds_1 is interpreted as the maximum flooding surface (e.g., Pemberton and MacEachern, 1995; Zonneveld *et al*., 2001)

The HST consists of two shallowing upward parasequences. The first parasequence is composed of lagoonal lithofacies with *Ophiomorpha* isp., and lithofacies C (shoal) with *Diplocraterion parallelum*. The second parasequence is formed by lithofacies B with *Ophiomorpha* isp. and lithofacies A with *Psilonichnus*. Therefore the changes from the Cruziana *ichnofacies* to the *Psilonichnus ichnofacies* demonstrate shallowing in depth at the end of the HST (e.g., Pemberton *et al*., 1992a; Pemberton & MacEachern, 1995).

In DS_2, the TST begins with lithofacies D (red algal packstone) and *Diplocraterion* that shows this lithofacies was deposited under near shoal condition in a high energy regime. *Diplocraterion* was gradually replaced by *Ophiomorpha* isp. in lithofacies D. Although *Ophiomorpha* isp. is common in shallow water (Pollard *et al*., 1993), it is also present in deeper facies too (Tchoumatchenco and Uchman, 2001; Uchman, 2007). *Diplocraterion parallelum* also has similar condition, because it could have formed in high energy shoal (Fürsich *et al*., 2006) and deeper facies (Seilacher, 2007). Nonetheless *Diplocraterion* dominated in deeper part rather than *Ophiomorpha* (Seilacher, 2007). Thus, the change in abundance from *Diplocraterion* to *Ophiomorpha* within the deep red algal packstone lithofacies could be interpreted as depth variations during the deposition of lithofacies D. The top surface of *Diplocraterion parallelum* bed is interpreted as the maximum flooding surface (MFS). Five shallowing upward parasequences including lithofacies D, C, and B represent the HST stage. Finally after this period, regression occurred in this area and the red beds of the Pestehleigh Formation were deposited in a fluvial depositional system (Moussavi-Harami, 1993). This fluctuation of sea level in the study area during the Late Maastrichtian time closely correlates with the global sea level curve published by Haq *et al*. (1987) (Fig. 7).

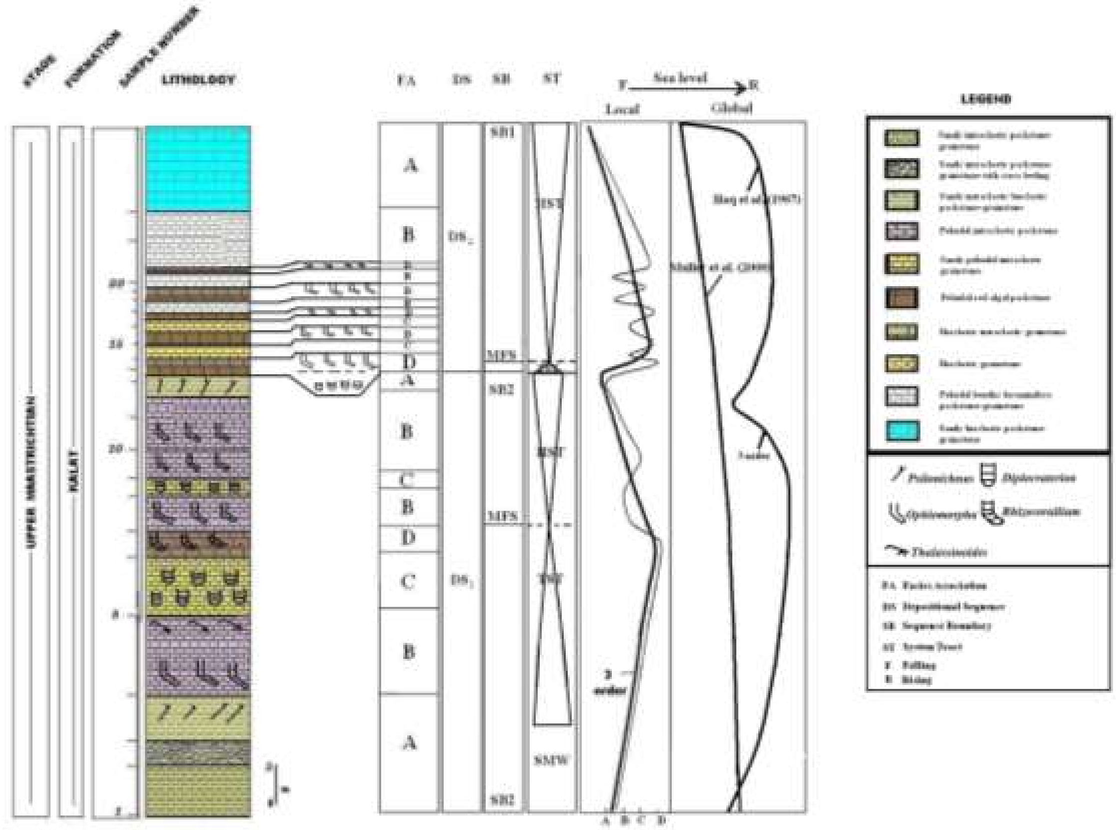

Figure 7: Stratigraphic column and sequence stratigraphy of the Kalat Formation in the central Kopeh- Dagh Basin.

Conclusions

This study shows that the combination of ichnofacies and lithofacies analysis is a useful tool in high-resolution sequence stratigraphy and reconstruction of depositional environments.

Four lithofacies of a ramp-type carbonate platform were identified in the Upper Maastrichtian deposits of the central Kopeh- Dagh Basin (NE Iran), including tidal flat (A), lagoon (B), bar (C) and open marine (D) environments, comprising the *Psilonichnus* and *Cruziana ichnofacies*. Two depositional sequences (DS_1 and DS_2) were recognized in this stratigraphic interval. DS_1 is composed of shelf margin wedge with no trace fossils, while TST contains various trace fossils and the MFS with pelloidal algal packstone as well as *Rhizocorallium jenense*. The HST is characterized by shallowing-upward lithofacies with elements of the *Cruziana ichnofacies* and subordinate of the *Psilonichnus ichnofacies* at the top. The second depositional sequence (DS_2) begun with deeper water lithofacies of pelloidal red algal packstone containing *Diplocraterion parallelum*. The MFS was recognized by the occurrence of a *Diplocraterion* bed, and an early HST was interpreted by the occurrence of a *Ophiomorpha* isp. in a similar lithofacies.

Acknowlegements

We would like to thank Professor Seilacher and Professor Fursich for helpful comments and suggestions on trace fossil identification. We thank Drs. Dashtgard and Heydari for constructive comments and suggestions. We are also grateful to Professor Pemberton for giving access to additional information on ichnofacies and sequence stratigraphy. We would like to thank Dr. Robert L. Brenner of Iowa University for reviewing the manuscript.

References

Adachi, N., Ezaki, Y., Liu, J., 2004. The origin of pelloids immediately after the end Permian extinction, Guizhou Province, South China. Sedimentary Geology 146, 161-178.

Afshar-Harb, A., 1969. A brief history of geological exploration and geology of Sarakhs area and Khangiran gas field (in Persian). Bulletin of Iranian Petroleum Institute 37, 86-96.

Afshar-Harb, A., 1979. The stratigraphy, tectonics and petroleum geology of the Kopeh- Dagh region, northern Iran. Unpublished Ph.D Thesis, Imperial College of Sciences and Technology, University of London, London, 316 .

Afshar-Harb, A., 1982. Geological Map of Dareh Gaz 1:250000. Geological Survey & Mineral Exploration of Iran. 1 Sheet.

Afshar-Harb, A., 1994. Geology of the Kopeh- Dagh Iran (in Persian). Geological Survey of Iran, Tehran, 265.

Alavi, M., Vaziri, H., Seyed-Emami, K., Lasemi, Y., 1997. The Triassic and associated rocks of the Aghdarband area in central and northeastern Iran as remnant of the southern Turanian active continental margin. Geological Society of America Bulletin 109, 1563-1575.

Berberian, M., Kings, G.C.P., 1981. Towards a paleogeography and tectonic of Iran. Canadian Journal of Earth Sciences 18, 210-265.

Cadjenovic, D., Kilibarda, Z., Radulovic, N., 2008. Triassic to Late Jurassic evolution of the Adriatic carbonate platform and Budva Basin, Southern Montenegra. Sedimentary Geology 24, 1-17.

Campbell, K.A., Nesbitt, E.A., 2000. High-resolution architecture and paleoecology of an active margin, storm-flood influenced estuary, Quinault Formation (Pliocene) Washington. Palaios 15, 551-576.

Catuneanu, O., 2006. Principle of Sequence Stratigraphy. Elsevier, Amsterdam. 375.

Coffey, B.P., Read, J.F., 2004. Mixed carbonate-siliciclastic sequence stratigraphy of a Paleogene transition zone continental shelf, Southeastern USA. Sedimentary Geology 166, 21-57.

Cornish, F. G., 1986. The trace-fossil *Diplocraterion*; evidence of animal sediment interactions in Cambrian tidal deposits. Palaios 1, 478- 491.

Flügel, E., 2004. Microfacies of Carbonate Rocks Analysis: Interpretation and Application (2ed ed.), Springer-Verlag Berlin Heidelberg, 976.

Fürsich, F.T., 1974. On *Diplocraterion Torell* and the significance of morphological features in vertical, spreiten-bearing, U shaped trace fossils. Journal of Paleontology 48, 952-962.

Fürsich, F.T., 1975. Trace fossils as environmental indicators in the Corallian of England and Normandy. Lethaia 8, 151-172.

Fürsich, F.T., 1981. Invertebrate trace fossils from the Upper Jurassic of Portugal. Communicoes Servicos Geologicos de

Portugal 67, 53-168.

Fürsich, F.T., Wilmsen, M., Seyed-Emami, K., 2006. Ichnology of Lower Jurassic beach deposits in the Shemshak Formation at Shahmirzad, southeastern Alborz Mountains, Iran. Facies 52, 599-610.

Gingras, M.K., MacEachern, J.A., Pemberton, S.G., 1998. A comparative analysis of the ichnology of wave- and river-dominated Allomembers of the Upper Cretaceous Dunvegan Formation. Bulletin of Canadian Petroleum Geology 46, 51-73.

Gingras, M.K, Rasanen, M.E., Pemberton, S.G., Romeo, L.P., 2002. Ichnology and sedimentology reveal depositional characteristics of bay-margin parasequences in the Miocene Amazonian foreland basin. Journal of Sedimentary Research 72, 871- 883.

Golonka, J., 2004. Plate tectonic evolution of the southern margin of Eurasia in the Mesozoic and Cenozoic. Tectonophysics 381, 235-273.

Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. Science 235, 1156-1167.

Kalantary, A., 1987. Biofacies relationship of the Kopeh- Dagh region: National Iranian Oil Company. Exploration and Production Group. Tehran. 1 sheet.

Mahboubi, A., Moussavi-Harami, R., Mansouri-Daneshvar, P., Najafi, M., 2006. Upper Maastrichtian depositional environments and sea level history of the Kopeh-Dagh intracontinental basin, Kalat Formation, NE Iran. Facies 52, 237-248.

Malpas, J. A., Gawthorpe, R. L., Pollard, J. E., Sharp, I. R., 2005. Ichnofabric analysis of the shallow marine Nukhul Formation (Miocene), Suez Rift, Egypt implications for depositional processes and sequence stratigraphic evaluation. Palaeogeography, Palaeoclimatology, Palaeocology 215, 239-264.

Masse, J.P., Fenerci, M., Pemarcic, E., 2003. Palaeobathymetric reconstruction of peritidal carbonates, Late Barremian, Urgonian, Sequences of Provence (SE France). Palaeogeography, Palaeoclimatology, Palaeoecology 200, 65-81.

Monaco, P., Caracuel, J. E., Giannetti, A., Soria, J. M., Yebenes, A., 2007. *Thalassinoides* and *Ophiomorpha* as cross-facies trace fossils of crustaceans from shallow-to-deep-water environments: Mesozoic and Tertiary examples from Italy and Spain: 3rd Symposium on Mesozoic and Cenozoic Decapod Crustaceans. Fascicolo 2, 4.

Moussavi-Harami, R., 1993. Depositional history and paleogeography of the Lower Paleocene red beds in eastern Kopeh-Dagh Basin northeastern Iran. Journal of Science I.R.Iran 4, 126-143.

Moussavi - Harami, R., Brenner, R.L., 1992. Geohistory analysis and petroleum reservoir characteristics of Lower Cretaceous (Neocomian) sandstone, eastern portion of Kopeh- Dagh Basin, northeast Iran. American Association of Petroleum Geologiest Bulletin 76, 1200-1208.

Myint, M., 2001. *Psilonichnus quietis* isp. nov. from the Eocene Iwaki Formation, Shiramizu Group, Joban Coal Field, Japan. Ichnos 8, 1-14.

Nader, F.H., Abdel-Rahman, A.M., Haidar, A.T., 2006. Petrographic and chemical traits of Cenomanian platform carbonates (Central Lebanon), implications for depositional environments. Cretaceous Research 27, 689-706.

Nesbitt, E.A., Campbell, K.A., 2002. A new *Psilonichnus* ichnospecies attributed to mud-shrimp Upogebia in estuarine settings. Journal of Paleontology 76, 892-901.

Nesbitt, E.A., Campbell, K., 2006. The paleoenvironmental significancance of *Psilonichnus*. Palaios 21, 187-196.

Obon-Ikuenobe, F.E., Obi, C.G., Joramill, C.A., 2005. Lithofacies, palynofacies, and sequence stratigraphy of Paleogene strata in southeastern Nigeria. Journal of Asian Earth Science 41, 79-101.

Olivier, N., Pittet, B., Werner, W., Hantzpergue, P., Gaillard, C., 2008. Facies distribution and coral-microbialite reef development on a low-energy carbonate ramp (Chay Peninsula, Kimmeridgian, western France). Sedimentary Geology 205, 14-33.

Oloriz, F., Rodriguez-Tovar, J., 2000. *Diplocraterion*, A useful marker for sequence stratigraphy and correlation in the Kimmeridgian Jurassic (Prebetic zone, Betic Cordillera, southern Spain. Palaios 15, 546-552.

Pemberton, S.G., and Frey, R.W., 1985. The Glossifungites ichnofacies: modern examples from the Georgia coast, USA, in: Curran, H.A.(Ed.), Biogenic Structures, Their Use in Interpreting Depositional Environments. SEPM Special Publication 35, 237-259.

Pemberton, S.G., Maceachern, J.A., Frey, R.W., 1992a. Trace fossil facies models: environmental and allostratigraphic significance, in: Walker, R.G., and James, N. (Eds.), Facies Models: Response to Sea Level Change. Geological Association of Canada, 47-72.

Pemberton, S.G., MacEachern, J.A., 1995. The sequence stratigraphic significance of trace fossils: examples from the Cretaceous foreland basin of Alberta, Canada, in: Van Wagoner, J.C., and Bertram, G. (Eds.), Sequence Stratigraphy of Foreland Basin Deposits, Outcrop and Subsurface Examples from the Cretaceous of North America. American Association of Petroleum Geologists Memoirs 64, 429-475.

Pemberton, S.G., MacEachern, J.A., Saunders, T., 2004. Stratigraphic applications of substrate-specific ichnofacies: delineating discontinuities in the rock record, in: McIlroy, D. (Ed.), The Application of Ichnology to

Palaeoenvironmental and Stratigraphic Analysis. Geological Society Special Publications, London, 228, 29-62.

Pemberton, S.G., Reison, G.E., MacEachern, J.A., 1992b. Comparative ichnological analysis of late Albian estuarine valley-fill and shelf-shoreface deposits, Crystal Viking Field, Alberta, in: Pemberton, S.G. (Ed.), Applications of Ichnology to Petroleum Exploration., SEPM Core Workshop 17, 291-317.

Pemberton, S.G., Spila, M., Pulham, A.J., Saunders, T., MacEachern, J.A., Robbins, D., Sinclair, I.K., 2001. Ichnology and sedimentology of shallow to marginal marine systems. Geological Association of Canada. Short Course Note 15.

Pollard, J. E., Goldring, R., Buck, S.G., 1993. Ichnofabrics containing *Ophiomorpha*: significance in shallow water facies interpretation. Journal of the Geological Society 150 (1), 149-169.

Robaszynski, F., Caron, M., Amedro, F., Dupuis, C., Hardenbol, J., Gonzalezdonoso, J.M., Linares, D., Gartner, S., 1994. Le Cénomanien de la région de Kalaat Senan (Tunisie centrale): Litho-, biostratigraphie et interprétationséquentielle. Revue de Paléobiologie, Genève 12, 351-505.

Rodriguez-Tavor, F. J., Perez-Valera, F., Perez-Lopez, A., 2007. Ichnological analysis in high-resolution sequence stratigraphy, The Glossifungites ichnofacies in Triassic succession from the Betic Cordillera (southern Spain). Sedimentary Geology 198, 293-307.

Ruttner, A.W., 1993. Southern borderland of Triassic Laurasia in north–east Iran. Geological Research 82,110-120.

Savrda, C.E., 1991. Ichnology in sequence stratigraphic studies: an example from the Lower Paleocene of Alabama. Palaios 6, 39-53.

Seilacher, A., 2007. Trace Fossil Analysis. Springer-Verlag, 225.

Şengor, A.M.C., 1987. Tectonics of the Tethysides: orogenic collage development in a collisional setting: Annual Review of Earth and Planetary Science 15, 213-244.

Şengor, A.M.C., Altiner, D., Cin, A., Ustaomer, T., Hsu, K.J., 1988. Origin and assembly of the Tethyside orogenic collage at the expense of Gondwana Land, in: Audley-Charles M.G., and Hallam, A. (Eds.), Gondwana and Tethys: Geological Society of London Special Publication 37, 119-181.

Smith, A.G., Smith, D.G., Funnel, B.M, 1994. Atlas of Mesozoic and Cenozoic Landmasses. Cambridge,99.

Tchoumatchenco, P., Uchman, A., 2001. The oldest deep-sea *Ophiomorpha* and Scolicia and associated trace fossils from the Upper Jurassic-Lower Cretaceous deep-water turbidite deposits of SW Bulgaria. Palaios 169, 85-99.

Thomas, S., Loser, H., Salos, R., 2008. Low- light and nutrient–rich coral assemblages in an Upper Aptian carbonate platform of the Southern Maestrat Basin (Iberian Chain, eastern Spain). Cretaceous Research 29, 1-26.

Uchman, A., 2007. Deep-sea trace fossils from the mixed carbonate-siliciclastic flysch of the Monte Antola Formation (Late Campanian-Maastrichtian), North Apennines, Italy. Cretaceous Research 28 (6), 1-25.

Wanke, H., Wanke, A., 2007. Lithostratigraphy of the Kalahari Group northeastern Nambia. Journal of African Earth Sciences 48, 314-328.

Wilson, V.P., 1975. Carbonate Facies in Geologic History. Springer-Verlag, 471.

Worsley, D., Mørk, A., 2001. The environmental significance of the trace fossil *Rhizocorallium jenense* in the Lower Triassic of western Spitsbergen. Polar Research 20, 37-48.

Zagrarni, M.F., Negra, M.H., Hanini, A., 2008. Cenomanian-Turonian facies and sequence stratigraphy, Bohloul Formation, Tunisia. Sedimentary Geology 18, 18-35.

Zonneveld, J.P., Gingras, M.K., Pemberton, S.G., 2001. Trace fossil assemblages in a Middle Triassic system, British Columbia. Palaeogeography, Palaeoclimatology, Palaeoecology 166, 249-276.