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ORIGINAL ARTICLE

Ichnological analysis of the Miocene marine deposits of Makran (SE Iran): implication for paleoenvironmental interpretations

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Abstract

The presence of trace fossils and their diversity in Miocene deposits of western Makran accretionary prism (SE Iran) was the center of this research. The trace fossil contents of Cheraghsuz and Sardasht (with Middle Miocene in age) and Gowharan (with Early Miocene in age) stratigraphic sections were analyzed. The recognized specimens of the Cheraghsuz section are *Gordia* isp., *Helminthopsis hieroglyphica*, *Helminthopsis abeli*, *Helminthorhaphe flexsuosa*, *Paleodictyon maximum*, and *Spirorhaphe involuta*. The Sardasht section is composed of *Gordia* isp., *Helminthopsis hieroglyphica*, *Helminthopsis abeli*, *Helminthorhaphe flexsuosa*, *Paleodictyon maximum*, *Paleodictyon majus*, *Paleodictyon* isp., *Spirorhaphe involuta*, *Helicolithus* isp., *Helicorhaphe tortilis*, and *Neonereites* isp.. In the Gowharan section, some gastropod trails, a giant and very well-preserved *Archaeonassa*-like ichnogenus, and ripple marks were observed. Majority of the recognized trace fossils are of the graphoglyptid group. The trace fossil contents of Cheraghsuz and Sardasht sections are compatible with *Nereites* ichnofacies; as graphoglyptids are thought to be indicative of oligotrophic conditions, the trace-producers are filter-feeder organisms that normally tend to take suspended nutrient materials in the water column, but due to lower sedimentation rate, the nutrient content is concentrated on the superficial part of the substrate; accordingly, the trace-makers prefer grazing and moving on the surface sediment to take their food. However, the exceptionally preserved trace fossils in Gowharan section should be formed in a tidal flat environment. In relation to the floor, it has recorded at least three shapes, including bi-lobed, uni-lobed and submerged forms. In addition, it could be observed that different trace fossils may be created by a single animal and different animals may create the same trace fossils.

Keywords Makran · Miocene ichnofauna · Flysch zone · Trace fossil · *Nereites* ichnofacies · Graphoglyptids

Introduction

Ichnology is widely regarded as a science at the interface between sedimentology and paleontology and has much to offer both subjects (McIlory 2008) because the ichnofossils are animal-originated sedimentary structures. The field of ichnology straddles the areas of sedimentology and paleontology, and displays multiple connections with disciplines within these areas and also with biology. Biogenic structures record the behavior of their trace-makers and provide valuable information for paleoecologic and paleoenvironmental analysis, and also have potential contributions to paleogeography. Trace fossils yield valuable insights into the paleoecology of ancient benthic communities and the environmental dynamics of depositional systems (Melchor et al. 2015).

Trace fossils can be assigned as important tools in recognition of paleoenvironments, paleoecology, sea-level changes, and so on, particularly when body fossils are scarce (Buatois and Mángano 2011; Luo et al. 2019). Trace fossils (including genera, ichnofacies, and ichnofabrics) are considered to be invaluable indicators of different aspects such as behaviors of benthic invertebrates, substrate consistency, oxygenation, salinity, hydrodynamic energy, paleoecological and paleoenvironmental conditions, key-stratigraphic surfaces, sequence-stratigraphy frameworks (Bayet-Goll et al. 2014, 2015; Paranjape et al. 2014; Villegas-Martín et al. 2014; Zhao et al. 2015; Solórzano et al. 2017; Urash and

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Savrda 2017; Zhang et al. 2018). Besides, they are useful in interpreting the sedimentary parameters, such as water turbidity, sedimentation rates, substrate consistency, salinity, and oxygenation of the substrates (Fan and Gong 2015).

Trace fossils, as behavioral records of organisms in the geological past, record organism–substrate interactions (Luo et al. 2016, 2019; Zhang et al. 2018), and represent the activities of both skeletonized and soft-bodied organisms (Luo et al. 2016; Zhang et al. 2018), thus serving as good proxies for larger processes operating within ancient trophic systems (Luo et al. 2016). Soft-bodied organisms account for a large percentage of the total biomass within marine ecosystems, but typically, they are only preserved in the form of trace fossils. Hence, trace fossils potentially provide more complete records of both epifaunal and infaunal organisms than do body fossils, thus facilitating the study of community structures and composition (Luo et al. 2017). Trace fossils record the behaviors of soft-bodied organisms that have null to very limited preservation potential in the fossil record. Furthermore, trace fossils provide valuable information regarding biotic perturbations that are not readily available through geochemical, sedimentological, and modeling-based research (Luo et al. 2016, 2017).

Most of the trace fossils, recovered from flysch zones, are of the graphoglyptid group. Based on Callow et al. (2013) turbidites contain the highest diversity in ichnofossils. They are relatively small and patterned trace fossils of different shapes and complexity, which include spirals (e.g., *Spirorhaphe*), meanders (e.g., *Cosmorhaphe* and *Helminthoida*), stars (e.g., *Lorenzinia* and *Glockeri*) and nets (e.g., *Paleodictyon*) (Seilacher 2007; Uchman, 2003). Each trace fossil is created in response to a special behavior of animals. Ekdale et al., (1984) recognized seven basic categories of behavior; they are as follow: (1) resting traces (cubichnia), (2) locomotion traces (repichnia), (3) dwelling structures (domichnia), (4) grazing traces (pascichnia), (5) feeding burrows (fodinichnia), (6) farming systems (agrichnia) and (7) escape traces (fugichnia).

In comparison with a large number of studies on the Paleozoic and Mesozoic trace fossils and their implications for paleoecological and paleoenvironmental interpretations, Cenozoic strata have been relatively unexplored from an ichnologic perspective. This study focused on the Miocene trace fossils investigated in the marine deposits of Makran (SW Iran).

Due to the presence of Flysch zones in the Makran basin (e.g., Burg et al. 2011; Dolati 2010; Crimes and McCall 1995; McCall et al. 1994; McCall and Kidd 1982), trace fossil specimens are vastly distributed in the area. The Miocene deposits in the western Makran are mostly composed of shale and sandstone; therefore, scarcity of body fossils is obvious. In this condition, trace fossils become more and more important. Here, even the poorest trace fossils become significant as a testimony for the presence and activities of animals and can reconstruct the paleoenvironmental conditions of the time.

In general, the Makran basin has received far less attention than other geological basins/units of Iran. Because of the morphologic characteristics of the study area and access to the Makran basin, the investigations are not as much as other parts of Iran. Amongst them, mostly seismic and tectonic investigations were done in the Makran basin. McCall and Kidd (1982) and McCall (1985) distinguished different geotectonic zones of the Makran basin. McCall (1983) studied Melanges of the Makran zone. In 1986, McCall and Simonian did the Makran project. McCall et al. (1994) used helicopter-borne to investigate carbonate deposition in accretionary prism settings of the Makran basin, based on coral limestones. Crimes and McCall (1995) recorded a diverse ichnofauna from Eocene–Miocene rocks of the Makran basin. As well, Abbasi (2000) worked on paleoichnology, lithostratigraphy, and sedimentary environments of Miocene deposits of eastern Makran. Dolati (2010), investigated the stratigraphy and structural geology across the Makran accretionary wedge in Iran. Burg et al. (2011) worked on the tectonic activity of the Makran basin. Ghaedi et al. (2016) studied the paleoenvironmental conditions of the Early Miocene corals of the western Makran in three stratigraphic sections (Tejek, Kermestan and Irer). Surprisingly, little information is available concerning the different paleontological and sedimentological properties of Makran. Likewise, detailed studies on the Miocene trace fossil contents of the Makran basin are scarce. The aim of this study is, therefore, to bridge this gap by the study of three Miocene stratigraphic sections in the Makran basin to analyze their trace fossils, and paleoenvironments (based on the ichnofauna) and to establish a basic framework for future studies.

This work would be important due to its trace fossil contents which increase the knowledge about ichnodiversity of the Makran basin; on the other hand, introducing the remarkably giant trace fossil in this investigation together with other obtained trace fossils can indicate a high potential for preservation of them in the Makran basin.

Geological settings

The geology and especially the tectonic structure of Iran are highly influenced by the development and history of the Tethyan (Paleotethys and Neotethys Oceans) region (Alavi 2004; Reichert 2007; Mohammadi 2020, 2021, 2022; Fig. 1). Iran represents a mosaic of continental blocks separated from each other by fold-and-thrust belts formed during the opening and closure of the Tethyan oceanic basins (Berberian and King 1981; Stampfli 2000; Shufeng et al. 2002; Stampfli and Borel 2002; Reichert

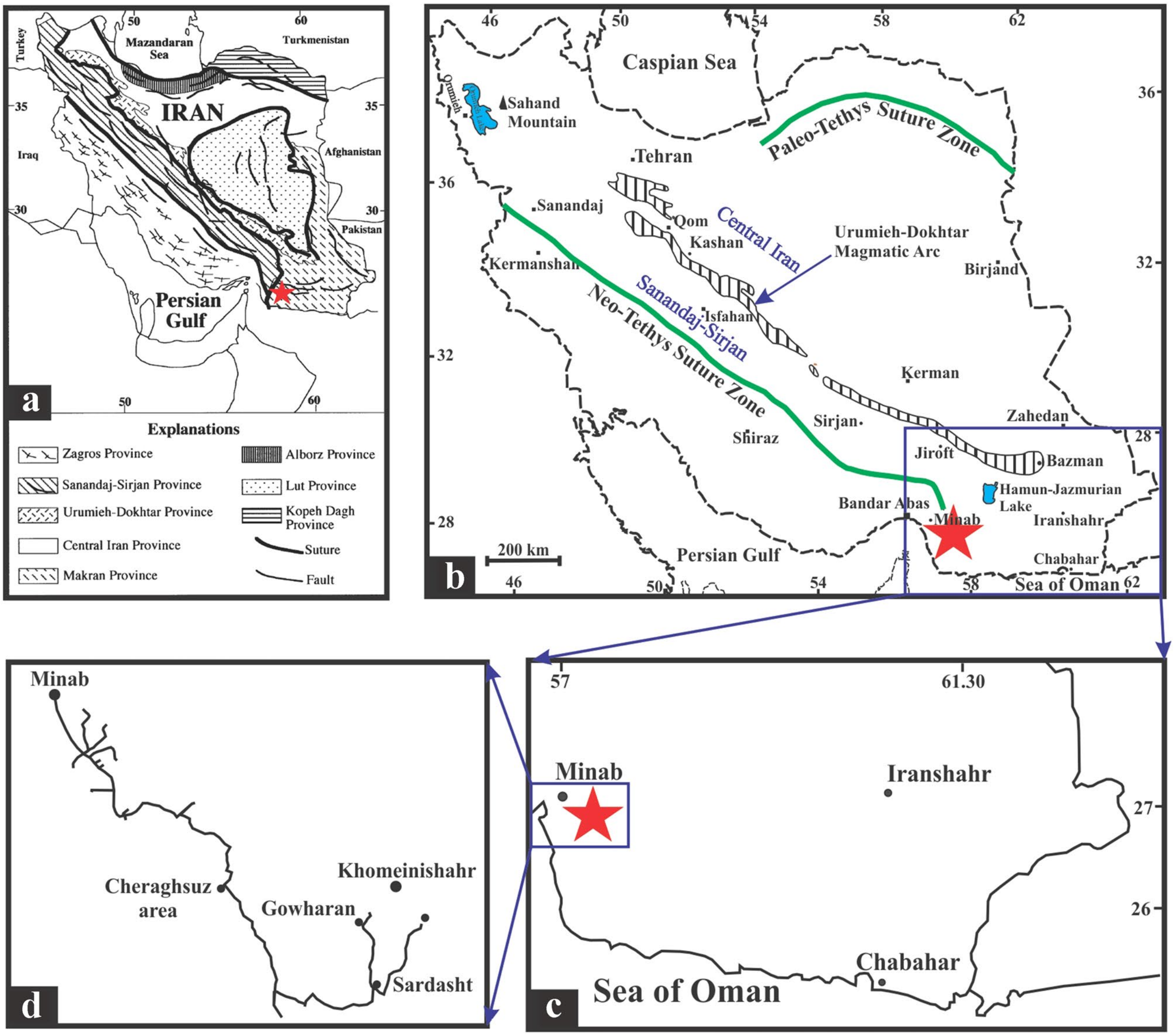

Fig. 1 **a** General map of Iran showing the eight geological provinces (modified from Heydari et al. 2003), **b** Map showing the distribution of Urumieh–Dokhtar Magmatic Arc and suture zones of Paleotethys and Neotethys in Iran (after Mohammadi et al. 2013; Mohammadi 2021; 2022), **c**–**d** Geographic situation and road map of the studied sections in western Makran (southeastern Iran). In **a**, **b**, and **c**, the studied area is shown by a red star

2007; Mohammadi 2020, 2021, 2022; Fig. 1). Iran is divisible into eight geological provinces; each one has its own distinct tectonic and sedimentary history. These provinces are (1) Zagros fold belt; (2) Sanandaj–Sirjan thrust belt; (3) Urumieh–Dokhtar magmatic arc; (4) Central Iranian province; (5) Alborz Range; (6) Kopeh Dagh basin; (7) Lut terrane; and (8) Makran accretionary prism (Stöcklin 1968; Heydari et al. 2003; Mohammadi 2020; Mohammadi et al. 2011, 2013, 2015; Fig. 1). Considering aerial view, the Makran basin extends from Oman sea coasts to Jazmurian depression. Its western limit is the Minab fault which separates the Makran and Zagros basins. The Makran basin continues to the Las Bela axis of Pakistan Balouchestan and is virtually 160,000 km^2 (Aghanabati 2004; Ghaedi et al. 2016). Based on McCall and Kidd (1982) and McCall (1985) the Makran basin could be divided into eight geotectonic zones. They are as follows: (1) Jazmurian Depression; (2) Spreading Zone; (3) Carbonate Fore-arc Zone; (4) Trench Zone; (5) Eocene–Oligocene Flysch Zone; (6) Oligocene–Miocene Flysch Zone; (7) Miocene Neritic Sediment Zone; and (8) Miocene–Pliocene Neritic-Continental Sediment Coastal Zone. Based on prevailing conditions on the Makran subduction zone, geological–stratigraphical units occasionally are not arranged in order (Aghanabati 2004). In the northernmost part of the Makran basin, oceanic crust and pelagic deposits of Late Cretaceous are exposed; while the youngest deposits of the Makran basin are loose sandstones of Plio-Pleistocene, especially in coastal areas (Aghanabati 2004; Ghaedi et al. 2016). The presence of conglomerates with serpentine boulders together with exotic blocks of ophiolite-melange in the Lower Flysch (wild flysch), and the transgression of the lower sandstone and conglomerate of Eocene flysch over the ophiolite-melange in the Jagin valley and Fanuj area of the Makran (Falcon 1974; Huber 1978) have been used as evidence to suggest that this flysch basin is floored by ocean crust (Berberian and King 1981). As we know, the most important feature of the Makran basin is its tectonic traits, especially the activity of accretionary prism. The Makran basin is affected by Oman subduction (Burg et al. 2011). There are no formal lithostratigraphic divisions in the Makran basin; so they are informally divided into different units. In the Early Miocene, deposits analysis depicts that shallow-water condition and shelf deposition were common and they were influenced by tides; on the other hand, the Middle Miocene was accompanied by deposition in the basin with marked high tectonic activities (Burg et al. 2011). The Miocene deposits in Makran basin are Tiab Sandstone, Kheku Sandstone, Gushi Marl, some lower parts of Tahtun Unit, Sabz Unit, Darkhunish Shale, Dar Pahn Unit, Band-e Chaker Unit, Vaziri Unit, Jaghin Unit, Shahr Pum Unit, Ab-e Shahr Unit, Dehirdan Unit and upper parts of Angohran Unit (Peterson and Rudzinskas 1982). In this investigation, Sabz Unit, Band-e Chaker Unit, and Angohran Unit were studied.

Cheraghsuz section samples were collected from the sandstone part of the Sabz Unit. The Sabz Unit is gypsiferous shale and silty shale, with minor sandstone and limestone (Peterson and Rudzinskas 1982). This Unit in Cheraghsuz section is composed of silty shales intercalated with medium to thick-bedded sandstone. Sole marks including load casts, flute casts, and grove casts are well-developed in sandstone facies of Sabz Unit in this section. The Sabz Unit consists of a flysch succession that mainly formed in deep ramp depositional environments rather than in troughs (Ghorbani 2019).

Sampling in the Sardasht section was done in thickly bedded sandstones of the Band-e Chaker Unit. This Unit is composed of thickly bedded sandstone with interbedded siltstone and shale, massively bedded sandstone, sandstone marker, and shaley facies (Peterson and Rudzinskas 1982).

In the Gowharan section, the marly sandstone layers of upper parts of the Angohran Unit were investigated. The Angohran Unit comprises rhythmic, thinly bedded sandstone and shale with minor siltstone and conglomerate, massively bedded sandstone and shale, with minor siltstone and shell beds, gray silty shale, with minor sandstone (Peterson and Rudzinskas 1982).

Materials and methods

The trace fossil specimens were sampled through the field trip to the western Makran. According to eight geotectonic zones of Makran, offered by McCall and Kidd, (1982) and McCall (1985), the sampling was focused on Oligocene–Miocene Flysch Zone and Miocene neritic molassic Zone; Cheragh-Suz area (26° 51´ N, 57° 22´ E), Sardasht City (26° 27´ N, 57° 53´ E) and Gowharan City (26° 34´ N, 57° 52´ E) were investigated (Fig. 1). The authors tried to collect all the specimens in the field to be studied in detail in the laboratory, but it is conspicuous that some of them could not be collected. Because they were too hard to be broken and be separated from source rock and too large or too heavy to be carried. However, all necessary characteristics were noted and photographed in the field. Besides, lithology, rock type, and sedimentary structures were investigated to determine the paleoenvironment. The collected samples were studied and photographed and finally were stored in the University of Isfahan.

Results and discussion

Systematic ichnology

Different sorts of trace fossils were observed during the field trip. As it is mentioned above, the Makran basin was affected by tectonic activity and the flysch basin. Most of the trace fossils are graphoglyptids which are produced in flysch basins. We tried to offer some examples for each ichnogenus. Reasonable, objective and concise ichnotaxonomy is the base of all ichnological analysis (cf. Knaust 2012). Ideal ichnotaxonomy should provide a high-resolution taxonomical framework for comprehensive sedimentological and paleoecological studies (Fan and Gong 2017). Recovered trace fossils are as follows:

***Gordia* Emmons (1844)**

Gordia isp. (Fig. 2a, b).

Description: This trace fossil is slender, thin (about 1–2 mm), long, smooth, unornamented, and unbranched; it has the same thickness throughout and bends in approximately irregular and curved direction and crosses itself in a horizontal surface and makes irregular loops. Its diameter is about 3 cm but sometimes it is much more.

Remarks: *Gordia* is a facies-crossing trace fossil that is known from marine and non-marine environments (Pickerill et al. 1984; Gaigalas and Uchman 2004). It has been recognized also from lacustrine, playa, levee, sheer, flood, and aeolian interdune deposits (Keighley 1996). Hofmann (1990) highlighted *Gordia* as an example of random behavior. He (1990) separated

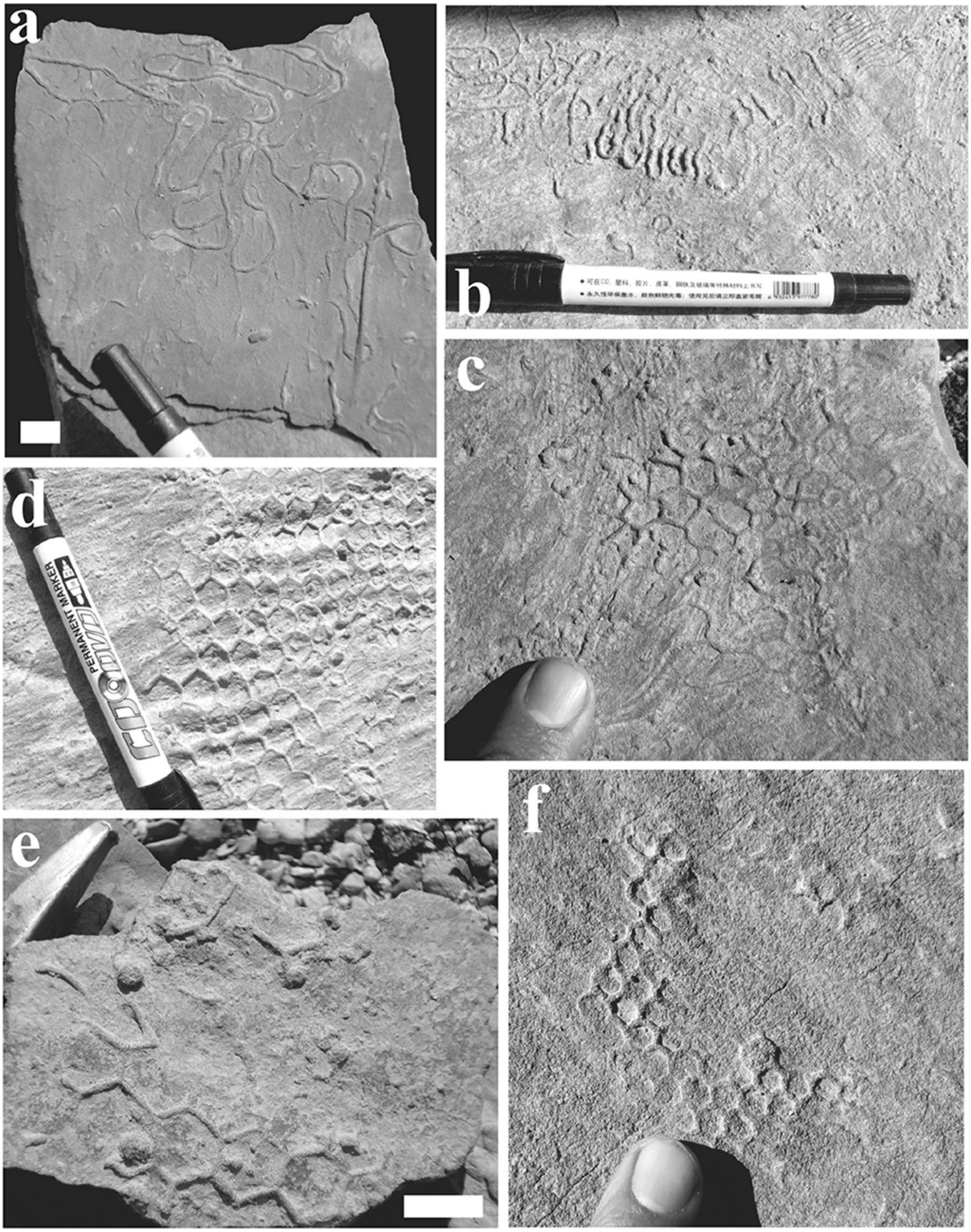

Fig. 2 Photographs showing selected trace fossils of the Makran **a** *Gordia* isp. (Cheraghsuz section, Sabz Unit), **b** *Helminthorhaphe flexuosa* (middle) converting to *Gordia* isp. (Left) (Sardasht section, Band-e Chaker Unit), **c** *Paleodictyon* isp. (Sardasht section, Band-e Chaker Unit), **d** *Paleodictyon maximum* (Sardasht section, Band-e Chaker Unit), **e** *Paleodictyon maximum* (Cheraghsuz section, Sabz Unit), **f** *Paleodictyon majus* (Sardasht section, Band-e Chaker Unit); scale bar is 1 cm

Gordia from *Helminthoidichnites*; although they are produced by the same trace-maker (Gaigalas and Uchman 2004). *Gordia* loops are the most characteristic feature while *Helminthoidichnites* display only occasional loops (Hofmann and Patel 1989). Gaigalas and Uchman (2004) believe that there are strong reasons for these two ichnogenera to be the synonym of each other. *Gordia* is an epichnion or shallow endichnion that occurs in different facies since the Proterozoic and throughout the

Phanerozoic (Wang et al. 2009). The taxonomy of Gordia was briefly discussed by Fillion and Pickerill (1990) and Buatois et al. (1998). Książkiewicz (1977) suggested that *Gordia* may be a feeding burrow or trail produced by polychaete worms. *Gordia* has commonly been interpreted by Li et al. (1997) as either a feeding or a locomotory trace produced by worms or gastropods. Aceñolaza and Buatois (1993), McCann (1994), Yang (1994), and Geyer and Uchman (1995) have considered this ichnogenus as a pasichnion or fodinichnion, produced by worms or worm-like organisms. *Gordia* isp. has a simple horizontal trail architectural pattern, reflecting unsophisticated feeding strategy or simple locomotion (Buatois and Mángano 2013; Buatois et al. 2017; Kilibarda and Schassburger 2018). It is reported from Upper Pleistocene varved clays in Lithuania (Gaigalas and Uchman 2004). Bayet-Goll et al. (2015) reported *Gordia* isp from the Upper Cretaceous Neyzar Formation, NE Iran.

Occurrence: Cheraghsuz and Sardasht sections.

Abundance: common.

Helminthorhaphe **Seilacher (1977)**

Helminthorhaphe flexuosa Uchman 1995 (Fig. 2b).

Description: This is a horizontal and unbranched meandering trace fossil which due to its strings low distance, slightly seems compressed and has 3–5 mm limbs distances. The second-order undulation in the string is also present. The strings thickness is 2–3 mm and is preserved in positive relief.

Remarks: *Helminthorhaphe flexuosa* is a common trace fossil in deep marine turbidites (Callow et al. 2013). Callow et al. (2013), believe that the full paleoenvironmental range of *Helminthorhaphe fluxuosa* in turbidite depositional systems has not been considered yet. *Helminthorhaphe* occurs from Early Cretaceous to Miocene (Uchman 2003). *Helminthorhaphe flexuosa* is generally considered as a predepositional agrichnion, although it may also have a simpler pascichnial origin (Buatois and Mángano 2011). It exhibits guided meandering graphoglyptid architectural design in a shallow-tier, representing farming trace fossils produced most likely by worms (Buatois and Mángano 2013; Buatois et al. 2017; Kilibarda and Schassburger 2018).

Helminthorhaphe flexuosa is reported from Upper Cretaceous/Paleogene of Jamaica and Iran (Pikerill and Mitchell, 1999; Bayet-Goll et al. 2014, respectively), Upper Cretaceous to Miocene (Fan et al. 2017) and Miocene of Turkey (Nielsen et al. 2012).

Occurrence: Cheraghsuz and Sardasht section.

Abundance: common.

Paleodictyon **Meneghini in Murchison (1850)**

Paleodictyon isp. (Fig. 2c).

Description: it is an irregular hexagonal, pentagonal, and square net with 0.3–1 cm mesh size and its string diameter is 1–2 mm. It is preserved in positive relief.

Remarks: *Paleodictyon* Meneghini (1850) is a distinct trace fossil preserved commonly as casts on the sole of fine- to medium-grained turbidites (Peruzzi 1880). *Paleodictyon* belongs to the group of trace fossils known as graphoglyptids, which includes a large number of ichnotaxa and are highly organized trace fossils normally found as casts on the lower surface of distal turbidites (Wetzel 2000; Seilacher 2007). Trace-makers of Paleodictyon are inferred to be farming microbes and are, therefore, included in the ethologic group of agrichnia. Paleodictyon was constructed in many environments during the early Paleozoic (Cambrian) (Uchman 2003) and has been found in deep-water turbidite deposits from the Late Cretaceous to Paleogene (Monaco 2008). *Paleodictyon* ispp. ranges from Cambrian to Miocene (Uchman 2003). *Paleodictyon nodosum* is a modern *Paleodictyon* ichnospecies (Seilacher 2007). *Paleodictyon* isp reported by Fürsich et al. (2007) from the Triassic–Jurassic shallow marine deposits of Iran, by Monaco (2008) from the Oligo-Miocene turbidites of Italy, by Lan and Chen (2010) from the Middle Permian deposits of Western Australia, by Bayet-Goll et al. (2014) from the upper Maastrichtian–Paleocene Amiran Formation, W Iran, by Zhao et al. (2015) from Early Triassic of South China, and by Kilibarda and Schassburger (2018) on soles of turbidite beds in the Adriatic Flysch (Central Mediterranean; middle Eocene–Middle Miocene).

Occurrence: Sardasht section.

Abundance: rare.

Paleodictyon maximum Eichwald (1868) (Fig. 2d, e).

Description: it is a hexagonal net with 0.8–1 cm mesh size and its string diameter is 1–2 mm. It is preserved as a positive relief.

Remarks: ichnologists consider different criteria for the identification of Paleodictyon species. For instance, Ksiazkiewicz (1977) and Ksiazkiewicz (1970) considered mesh size, regularity, and thickness; while mesh shape was very significant for Seilacher (1977). Uchman (1995), offered a simple diagram and defined morphologic distinction of the ichnospecies *Paleodictyon* based on the morphometric parameters of tunnel diameter and maximum mesh size. He also believes that in the Miocene, forms with broad tunnels are common. Vaziri and Fursich (2007) reported this ichnogenus from Triassic of Nakhlak area in Iran.

Occurrence: Cheraghsuz and Sardasht section.

Abundance: common.

Paleodictyon majus Meneghini in Perruzi (1880) (Fig. 2f).

Description: it is a hexagonal net with 0.5–0.7 cm mesh size and its string diameter is 1–2 mm. It is preserved as a positive relief.

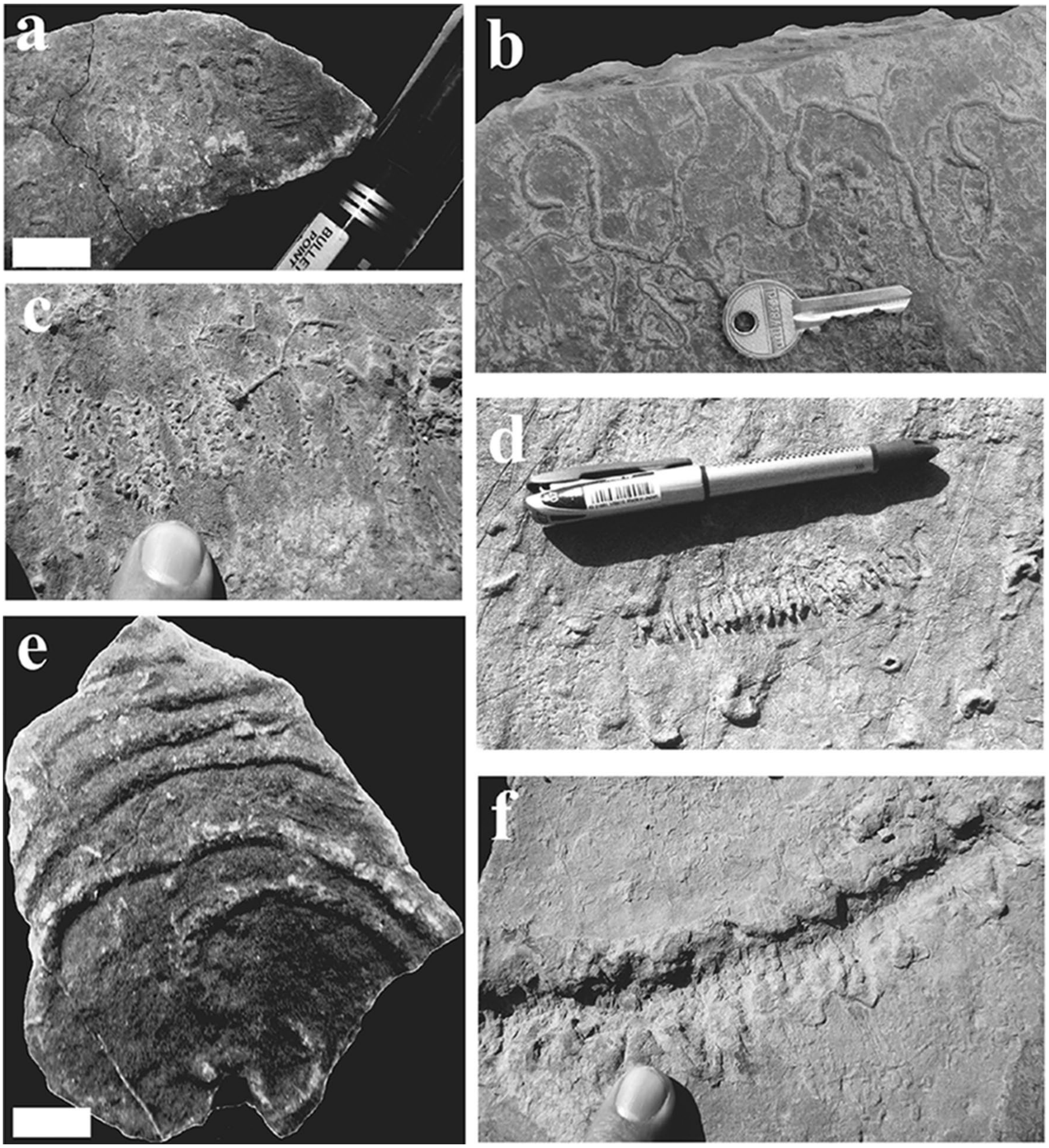

Fig. 3 Photographs showing selected trace fossils of the Makran **a** *Helminthopsis abeli* (Cheraghsuz section, Sabz Unit), **b** *Helminthopsis hieroglyphica* (Cheraghsuz section, Sabz Unit), **c** *Helicolithus* isp. (Sardasht section, Band-e Chaker Unit), **d** *Helicorhaphe tortilis* (Sardasht section, Band-e Chaker Unit), **e** *Spirorhaphe involuta* (Cheraghsuz section, Sabz Unit), **f** cf. *Neonereites* isp. (Sardasht section, Band-e Chaker Unit); scale bar is 1 cm

Remarks: it is reported from Eocene turbiditic deposits of Spain (Rodriguez-Tovar et al. 2010). As well, Bayet-Goll et al. (2014) reported *Paleodictyon majus* from the upper Maastrichtian–Paleocene Amiran Formation, W Iran.

Occurrence: Sardasht section.

Abundance: common.

Helminthopsis Heer (1877)

Helminthopsis abeli Ksiazkiewicz (1977) (Fig. 3a).

Description: it is unbranched and cylindrical tubes which bends and show sinuous and meandering windings with no self-crossing; it develops in a parallel situation to the bedding plane and shows irregular curves. Its meandering trail fades in some parts of the direction and creates horseshoe segments (C-shaped). The trails' thickness is about 2 mm.

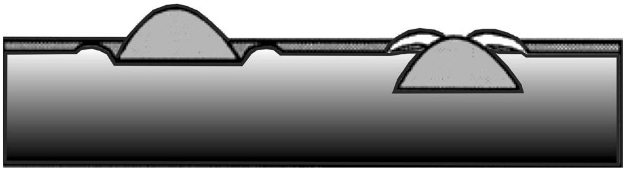

Fig. 4 The morphology of *Archaeonassa* depends on how deeply the animal submerged in the sediment. Effect of the animal in the morphology of *Archaeonassa* (redrawn after Jensen 2003)

Remarks: *Gordia* can be distinguished from *Helminthopsis* by the presence of crossovers (Wang et al. 2009). In contrast to *Gordia* and *Helminthoidichnites*, *Helminthopsis* has no loops (Hofmann and Patel 1989). *Helminthopsis* is a eurybathic and facies-crossing trace fossil that is common in flysch deposits (Crimes and McCall 1995; Fillion and Pickerill 1990; Ksiazkiewicz 1977) and could be observed in shallow and deep marine and non-marine environments (Pattinson 2005). It is a feeding burrow produced at shallow depth within sediment rich in nutrients (Wetzel and Broomley 1996). It is a pre-depositional pascichnion (Buatois and Mángano 2011) probably made by polychaete annelids (Książkiewicz 1977). Similar to *Gordia*, *Helminthopsis* also reveals a simple horizontal trail architectural pattern, reflecting unsophisticated feeding strategy or simple locomotion (Buatois and Mángano 2013; Buatois et al. 2017; Kilibarda and Schassburger 2018). It is reported from Ordovician and Eocene of Spain (Rodriguez-Tovar et al. 2010; Acenolaza and Gutierrez-Marco 1998), Carboniferous of Canada (Keighley and Pickerill 1997), Triassic of Nakhlak area in Iran (Vaziri and Fursich 2007), Upper Cretaceous Neyzar Formation, NE Iran (Bayet-Goll et al. 2015), and upper Maastrichtian–Paleocene Amiran Formation, W Iran (Bayet-Goll et al. 2014).

Occurrence: Cheraghsuz and Sardasht sections.

Abundance: rare.

Helminthopsis hieroglyphica Heer in Maillard (1887) (Fig. 3b).

Description: it is an unbranched meandering which demonstrates wide and irregular sinuous with 2–3 mm thickness. The trail can be completely seen and traced through the surface and has no loops. Therefore, it does not create horseshoe segments. As the trail bends, the sub-parallel direction to each other could be observed.

Remarks: It is reported from Carboniferous of Canada (Keighley and Pickerill 1997), Upper Cretaceous/Paleogene of Jamaica (Pickerill and Mitchell 1999), Triassic of Nakhlak area in Iran (Vaziri and Fursich 2007), upper Maastrichtian–Paleocene Amiran Formation, W Iran (Bayet-Goll et al. 2014) and Upper Cretaceous Neyzar Formation, NE Iran (Bayet-Goll et al. 2015).

Occurrence: Cheraghsuz and Sardasht sections.

Abundance: common.

Helicolithus Azpeitia-Moros (1933)

Helicolithus isp. (Fig. 3c).

Description: *Helicolithus* is a meandering trace fossil that is composed of small dashes and dots. The dash-like traces are 1–2 mm and are preserved in positive relief.

Remarks: This ichnogenus ranges from Late Cretaceous to Miocene but it is also reported from Permian (Uchman 2003). It is also reported by Monaco (2008) from the Oligo-Miocene turbidites of Italy.

Occurrence: Sardasht section.

Abundance: rare.

Helicorhaphe Książkiewicz (1961)

Helicorhaphe tortilis Ksiazkiewicz 1970 (Fig. 3d).

Description: this trace is approximately straight and its length is about 10 cm; it is composed of some perpendicular accessory rows to the main direction. The secondary rows are cylindrical and parallel to each other. The thickness of each second row is about 1–2 mm and their distance to each other is almost the same.

Remarks: *Helicorhaphe* is a relatively rare graphoglyptid. It is known exclusively from deep marine turbiditic assemblages (Callow et al. 2013; Uchman and Wetzel 2011; Uchman 1998). This ichnogenus may indicate the deposit-feeding or gardening behavior of a vermiform organism (Callow et al. 2013). *Helicorhaphe* is reported from the Eocene of Poland (Cabrera et al. 2008), Miocene of Iran (Crimes and McCall 1995), and Late Cretaceous of Mexico (Callow et al. 2013). *Helicorhaphe*.

Occurrence: Sardasht section.

Abundance: rare.

Spirorhaphe Fuchs (1895)

Spirorhaphe involuta De Stefani 1895 (Fig. 3e).

Description: this trace is a spiraled horizontal trail; it coils regularly inward and after situating in the center of the created circle and making a central loop, comes back outward alongside the first coiling trend. Its total diameter is about 10 cm and its trail thickness is 2–3 mm and is preserved in positive relief.

Remarks: *S. involuta*. can be differentiated from the other two ichnospecies of *Spirorhaphe*, *S. azteca* Seilacher, and *S. graeca* Seilacher, by the presence of the central loop (Pickerill and Mitchell 1999). Seilacher (2007) believes that *Spirorhaphe involuta* is formed in multiple spiraling levels

Table 1 Ethological category of trace fossils and their relation to deposition

Ichnotaxa	Ethological category	Relation to deposition	Unit
Gordia isp.	Grazing	Post-depositional	Sabz and band-e chaker
Helminthopsis abeli	Grazing	Post-depositional	Sabz and band-e chaker
Helminthopsis hieroglyphica	Grazing	Post-depositional	Sabz and band-e chaker
Helminthorhaphe flexsuosa	Farming	Pre-depositional	Sabz and band-e chaker
Paleodictyon maximum	Farming	Pre-depositional	Sabz and band-e chaker
Paleodictyon majus	Farming	Pre-depositional	Band-e chaker
Paleodictyon isp.	Farming	Pre-depositional	Band-e chaker
Spirorhaphe involuta	Grazing	Pre-depositional	Sabz and band-e chaker
Helicolithus isp.	Grazing	Pre-depositional	Band-e chaker
Neonereites isp.	Grazing	Post-depositional	Band-e chaker
Giant *Archaeonassa*-like ichnospecies	Movement	Post-depositional	Angohran
Helicorhaphe tortilis	Feeding/farming	Pre-depositional	Band-e chaker

while *S. azteca* and *S. graeca* are formed in a horizontal plane and show no central loop. Besides, Fan et al. (2017) noted that *Spirorhaphe involuta* (Stefani) can be seen as a spiralled single meander structure, which is quite similar to the movement pattern of *Helminthorhaphe*. *Spirorhaphe* is a trace fossil that is almost related to the deep turbidite depositional system (Maceachern et al. 2007). According to Callow et al. (2013) who reported this ichnogenus from Late Cretaceous of Mexico, the trace-maker of *Spirorhaphe* is unknown but may represent a shallow-burrowing, deposit-feeding, or microbial gardening vermiform organism. It

Fig. 5 Giant *Archaeonassa*-like ichnogenus; and gastropod trails (right-up corner) which are from the same substrate; ripple marks could be seen in the left. The scale bars are 1 cm

occurs from Cretaceous to Miocene but some reports show its presence in Triassic and Ordovician (Uchman 2003).

Occurrence: Cheraghsuz and Sardasht section.

Abundance: common.

Neonereites Seilacher (1960)

cf. *Neonereites* isp. (Fig. 3f).

Description: this trace fossil is rough, horizontal, and unbranched borrow which is slightly curved; its roughness is observed in it and is preserved in negative relief. The diameter is about 1–1.5 cm throughout the trail.

Remarks: On a worldwide scale, the ichnogenera *Gordia*, *Neonereites*, and *Planolites* first appear in the late Precambrian (Crimes 1987; Gibson 1989). This ichnogenus is reported in the Upper Ordovician of Iran by V. Moghaddam and Taheri (2003). It is reported from different ages by different authors (Howard III 1976; Bhargava and Bassi 1988; Gibson 1989; Greb and Chesnut 1994).

Occurrence: Sardasht section.

Abundance: rare.

Archaeonassa Fenton and Fenton (1937)

Giant *Archaeonassa*-like ichnospecies (Figs. 4, 5).

Description: this trace fossil is a giant one and is exceptionally preserved. This is a crawling trail and its thickness is about 15 cm and its diameter is approximately 4 m. Usually, this ichnogenus coils and intersects itself. It is bi-lobed and consists of a regular furrow and two lateral ridges.

Remarks: furrow is rarely smooth, mostly crossed by rounded wrinkles (Hantzschel 1975). The morphology of this type of trace fossil will depend on how deeply the animal submerged in the sediment (Jensen 2003) (Fig. 4). Neoproterozoic trace fossils of this type have been reported as *Aulichnites* and *Nereites* (Jenkens 1995; Narbonne and Aitken 1990; Crimes and Germs 1982). The grooved trail flanked on both sides by rounded ridges is diagnostic of *Archaeonassa*. *Archaeonassa* is typically preserved in intertidal regimes where such traces may be abundant (Fenton and Fenton 1937), and it may also occur more rarely in shallow-marine environments. *Archaeonassa* is also known from continental environments (e.g., Buckman 1994; Buatois and Mángano 2002). Yochelson and Fedonkin (1997) noted that, although this trace fossil was originally attributed to movement by a gastropod, the type occurrence should not be used as evidence of activity by Gastropoda. However, Buckman (1994) noted that it can be produced by various invertebrates, including mollusks and arthropods (Luo et al. 2017).

Occurrence: Gowharan section.

Abundance: rare.

Discussion

Three stratigraphic sections were sampled in the western Makran (SE Iran). Considering their age, they belong to the Early and Middle Miocene (Peterson and Rudzinskas 1982). Cheraghsuz and Sardasht sections are Early Miocene deposits and the Gowharan section is Middle Miocene in age. Each one of them has its own trace fossils content and characteristics. Cheraghsuz section comprises *Gordia* isp., *Helminthopsis abeli*, *Helminthopsis hieroglyphica*, *Helminthorhaphe flexuosa*, *Paleodictyon* isp., *Spirorhaphe involuta*. Sardasht section contains *Gordia* isp., *Helicolithus* isp., *Helicorhaphe tortilis*, *Helminthopsis hieroglyphica*, *Helminthorhaphe japonica*, cf. *Neonereites* isp., *Paleodictyon* isp., *Spirorhaphe involuta*. The Gowharan section which is Middle Miocene in age, has exposed ripple marks, massive, strange, and very well-preserved *Archaeonassa*-like trace fossil, accompanied by some gastropoda trails. This trace fossil is unique in the Makran basin or even in Iran or the world; because such giant trace fossils need many different preservation traits to eventually be exposed in an appropriate condition. Every kind of weathering or erosion can destroy and change layers' surface and consequently destroy trace fossils. Smaller trace fossils could be preserved better than bigger ones. The bigger trace fossils may be affected by joints, fractures, and sliding. On the other hand, due to their big size, the covering with subsequent sediments may take more time with less preservation.

All obtained trace fossils in the studied sections are horizontal to bedding and no vertical trace fossil was seen. Bedding-plane-parallel data is used to enhance geological interpretations—often by elucidating the distribution and morphology of biogenic structures within and between beds and by fostering identification of ichnospecies, ichnofacies, and ichnofabric (e.g., Bromley 1996; McIlroy 2004; Marenco and Hagadorn 2018). Bedding planes are particularly critical for analyzing trace fossil assemblages in which bed-parallel structures are abundant, such as in restrictive environmental settings (e.g., Savrda et al. 1984; Wignall 1993) or post-extinction intervals (e.g., Zhao et al. 2015; Luo et al. 2016; Marenco and Hagadorn 2018). Each one of the obtained trace fossils has its special behavior and relation to deposition (Table 1).

Virtually all fossil graphoglyptids as patterned and complex specimens occur on turbidite layers and most of them are interpreted as originally open, dominantly horizontal burrow systems that were partially eroded and filled with silt or sand brought to the seafloor in a sediment gravity flow (Seilacher 1962; Kern 1980). According to Bouma's classic cycle (Bouma 1962), the turbidite layers can be divided into five types of layers; due to being influenced by episodically turbid currents, each sequence contains fining-upward trend. In fact, each sedimentary turbidite cycle ends with organic-rich fine sediment (Abbasi 2020).

The trace-makers of *Gordia*, *Paleodictyon*, *Helminthopsis*, *Helminthorhaphe*, *Helicolithus*, *Spirorhaphe* are polychaets, worms or worm-like organisms (Wang et al. 2009; Ekdale 1980; Seilacher 1977; Uchman 1998; Bayet-Goll and Daraei 2017; Książkiewicz 1977; Buatois et al. 2017). Furthermore, graphoglyptids are thought to be indicative of oligotrophic conditions (Uchman 1998; Wetzel and Uchman 2001; Bayet-Goll and Daraei 2017). The mentioned trace-producers are filter-feeder organisms that normally tend to take suspended nutrient materials in the water column (Savrda 2007; Ghaedi and Yazdi 2016). Owing to lower sedimentation rate in the upper parts of the Bouma sequence, the nutrient content is concentrated on the superficial part of the substrate (Abbasi 2020). In such conditions, the trace-makers are impelled to start grazing and moving on the surface sediment to take their food and act as a deposit-feeder rather than just being filter-feeder organisms.

According to Seilacher (2007) some trace fossils such as *Paleodictyon*, *Oldhamia*, *Spirorhaphe*, *Spirophycus*, *Cosmorhaphe*, *Helminthoida*, and *Nereites* are indicators of *Nereites* ichnofacies. This ichnofacies is formed in soup-ground and soft-ground substrates (Maceachern et al. 2007). Previously, Crimes and McCall (1995) reported some trace fossils in Makran range as deep-water flysch such as *Helicorhaphe tortilis*, *Helminthoida crassa*, *Spirorhaphe involuta*, *Paleodictyon carpathicum*, *Paleodictyon majus*, *Paleodictyon gomezi*, *Cosmorhaphe* cf. *lobata* and so on. *Gordia* and *Helminthopsis* are facies-crossing trace fossils that may appear in different environments (Gaigalas and Uchman 2004; Crimes and McCall 1995; Fillion and Pickerill 1990; Pickerill et al. 1984; Ksiazkiewicz 1977). Therefore, based on the trace fossils content, ichnological distribution in Cheraghsuz and Sardasht sections belongs to the deep marine *Nereites* ichnofacies.

The exceptionally preserved trace fossil is unique in the Makran basin or even in Iran or the world; such giant trace fossils need many different preservation traits to eventually be exposed in an appropriate condition. Every kind of weathering or erosion can destroy and change layers' surface and consequently destroy trace fossils. Smaller trace fossils could be preserved better than bigger ones. The bigger trace fossils may be affected by joints, fractures, and sliding. On the other side, due to their big size, being covered with subsequent sediment may take more time with less preservation. As Jensen (2003) represented (Fig. 4), the trace-maker has acted differently and created bi-lobed and uni-lobed track, and as well it seems that it has submerged in the sediment.

The presence of small gastropod trails and very well-preserved and a giant *Archaeonassa*-like trace fossil accompanied with ripple marks in the Lower Miocene of Angohran Unit in the Gowharan section indicates that they are formed in an intertidal environment. Besides, Burg et al. (2011) tectonically suggested shallow water and shelf deposition, tidal influence, and emerging area to the north in the Early Miocene of the Makran basin. They also believe in the deposition in a basin with marked tectonic activity in the Middle Miocene of this basin. Besides, Ghaedi et al. (2016) noted that the existence of colonial corals and the occurrence of benthic foraminifera with hyaline walls indicate normal seawater conditions.

Compound trace fossils are made up of components that each represent an archetypical behavior of their own and therefore commonly occur isolated (Bertling et al. 2006); such compound trace fossils are also present in the Sardasht section. As an example, in one of the specimens, an animal has created *Helminthorhaphe flexuosa* and in the following it converts into *Gordia* isp. (Figs. 3, 1). In the Gowharan section, a giant *Archaeonassa*-like trace fossil is present; likewise, *Archaeonassa* specimens can be seen in the Early Triassic of Sanandaj–Sirjan basin in Benarizrh (northern Abadeh) (Ghaedi et al. 2008; personal observation of the first author). They are approximately similar but totally different in their size; it shows that different animals may create similar trace fossils.

Conclusion

Three stratigraphic sections (Cheraghsuz, Sardasht and Gowharan) of the Miocene deposits of western Makran accretionary prism (SE Iran) were studied to determine their trace fossil contents and paleoenvironments. Detailed field observations and ichnological analysis led to the following conclusions:

1. *Gordia* isp., *Helminthopsis hieroglyphica*, *Helminthopsis abeli*, *Helminthorhaphe flexsuosa*, *Paleodictyon maximum*, and *Spirorhaphe involuta* were recorded from both of the Cheraghsuz and Sardasht sections (with Middle Miocene in age). *Paleodictyon majus*, *Paleodictyon* isp., *Helicolithus* isp., *Helicorhaphe tortilis*, and *Neonereites* isp. were recognized only from the Sardasht section. In the Gowharan section, some gastropod trails, a giant and very well-preserved *Archaeonassa*-like ichnogenus, and ripple marks were observed.
2. Majority of the recognized trace fossils are of the graphoglyptid group.
3. The trace fossil contents of Cheraghsuz and Sardasht sections are compatible with Nereites ichnofacies.

4. The graphoglyptids are thought to be indicative of oligotrophic conditions, the trace-producers are filter-feeder organisms that prefer grazing and moving on the surface sediment to take their food.
5. The exceptionally preserved *Archaeonassa*-like ichnogenus is reported for the first time from the Makran basin and it is unique in the Makran basin or even in Iran or the world.
6. The giant and exceptionally preserved *Archaeonassa*-like ichnogenus in Gowharan section should be formed in a tidal flat environment.

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