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The trace fossil *Cardioichnus planus* from the lower Miocene of Algeria: the first record from Africa and a probable endemic tracemaker

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Abstract

Abundant *Cardioichnus planus* SMITH & CRIMES, 1983 have been reported for the first time from Africa. They occur in lower Miocene deep-marine deposits near Tiaret in northwestern Algeria. Morphological features of the trace, coupled with the spatial interrelationships between *Cardioichnus* and the echinoids documented in this area, provide evidence that the endemic spatangoid *Echinocardium nummuliticum* PÉRON & GAUTHIER, 1885 represents the tracemaker of the studied *C. planus*. *Cardioichnus* is known from the upper Jurassic to the Pleistocene and it has a wide geographic and environmental distribution.

1. INTRODUCTION

The ichnogenus *Cardioichnus* SMITH & CRIMES, 1983 embraces heart-shaped structures interpreted as a resting trace (cubichnia), produced by deposit-feeding, spatangoid irregular echinoids (known as heart urchins or potatoes) (SMITH & CRIMES, 1983; GIBERT & GOLDRING, 2008). It is common in deep- and shallow-marine deposits throughout the Meso-Cenozoic, from the Kimmeridgian (BOUCHEMLA et al., 2020) to the Pleistocene (MAYORAL et al., 2013; CARUSO & MONACO, 2015). This trace fossil is preserved as a convex or concave form, ovoid or subquadrate in shape, in positive hyporelief or negative epirelief on sandstone beds, and formed by two symmetrical broad lateral lobes connected at the depressed V-shaped region (SMITH & CRIMES, 1983; GIBERT & MARTINELL, 1995; KAPPUS & LUCAS, 2019).

Five ichnospecies of *Cardioichnus* are distinguished, including *C. planus* SMITH & CRIMES, 1983, the type ichnospecies; *C. ovalis* SMITH & CRIMES, 1983; *C. foradadensis* PLAZIAT & MAHMOUDI, 1988; *C. reniformis* MAYORAL & MUÑIZ, 2001 and *C. biloba* KAPPUS & LUCAS, 2019. Furthermore, this ichnogenus is found in association with locomotion traces, and it may co-occur with *Scolicia* (MAYORAL & MUÑIZ, 2001; UCHMAN, 2007a), and *Bichordites* (BERNARDI et al., 2010; MAYORAL et al., 2013; KAPPUS & LUCAS, 2019).

Here, the ichnospecies *C. planus* is recorded for the first time from Algeria and in the African continent. The interpretation of abundant *C. planus* from the lower Miocene Tiaret Marl Formation in western Algeria is presented and discussed. Furthermore, the spatangoid echinoid *Echinocardium nummuliticum* PÉRON & GAUTHIER, 1885 has been proposed as the probable producer of the studied *C. planus* specimens. Finally, a stratigraphic, palaeogeographic and palaeoenvironmental review of *Cardioichnus* and its ichnospecies is presented.

2. GEOLOGICAL SETTING AND LOCALITY

In the northwesternmost part of Algeria, the lower Chelif (e.g., NAIMI & CHERIF, 2021a; NAIMI et al., 2020), Tafna (e.g., NAIMI et al., 2021), the Tiaret (CHERIF et al., 2021) Neogene basins are located. They belong to the Tell Atlas (NAIMI & CHERIF, 2021b). The studied material comes from the Tiaret Marl Formation (CHERIF et al., 2021) of Sidi Ali Mellal section in the Tiaret basin (POLVÊCHE, 1960). The section is located some kilometeres to the northwest of the town of Tiaret (Fig. 1A–C). The lower Miocene Tiaret Marl Formation crops out widely in the Tiaret area. It overlies Visean rhyolites (POLVÊCHE, 1960), or Jurassic marine deposits (CHERIF et al., 2015, 2018; HALAMSKI & CHERIF, 2017; BELAID et al., 2020), and is overlain by the upper Miocene Tiaret Sandstone Formation (CHERIF et al., 2021).

The Tiaret Marl Formation has been attributed to the lower Miocene on the basis of a foraminiferal assemblage including *Cibicides mexicanus*, *C. pseudoungerianus*, *Globigerinoides sacculiferus irregularis*, *G. triloba*, *Nonion pompilioides*, *Orbulina universa*, *Pullenia bulloides* and *Uvigerina rustica* (POLVÊCHE, 1960; CHERIF et al., 2021). In Sidi Ali Mellal section, the Tiaret Marl Formation overlies the Tardi-Hercynian rhyolites and it has been subdivided into two main units (CHERIF et al., 2021).

Ichnological and sedimentological studies allowed the attribution of this formation to a deep-sea fan system, dominated by graphoglyptid trace fossils which characterize the turbidite successions and the *Nereites* ichnofacies (CHERIF et al., 2021). Moreover, these trace fossils have been subdivided into three ichnoassemblages corresponding to the *Nereites*, *Paleodictyon*, *Ophiomorpha rudis* ichnosubfacies. The trace fossil assemblage reported from this formation includes *Cardioichnus* isp., cf. *Chondrites* isp., *Cosmorhaphe* isp., *Desmograpton* isp., *Gordia* isp., *Helminthorhaphe* isp., *Helminthopsis* isp., cf. *Megagrapton* isp., *Nereites* isp., *Ophiomorpha* isp., *O. annulata*, *O. rudis*, *Palaeophycus* isp., *Paleodictyon majus*, *P. maximum*, *P. minimum*, *P. miocenicum*, *P. strozzii*, cf. *Planolites* isp., *P. montanus*, *Scolicia* isp., *S. prisca*, *S. vertebralis*, *Tisoa siphonalis*, *Tubulichnium* cf. *incertum*, *Urohelminthoida appendiculata* and *Zoophycos* isp. In the Sidi Ali Mellal section, the ichnoassemblage of the first unit contains the trace fossil *Cardioichnus* (Fig. 1D).

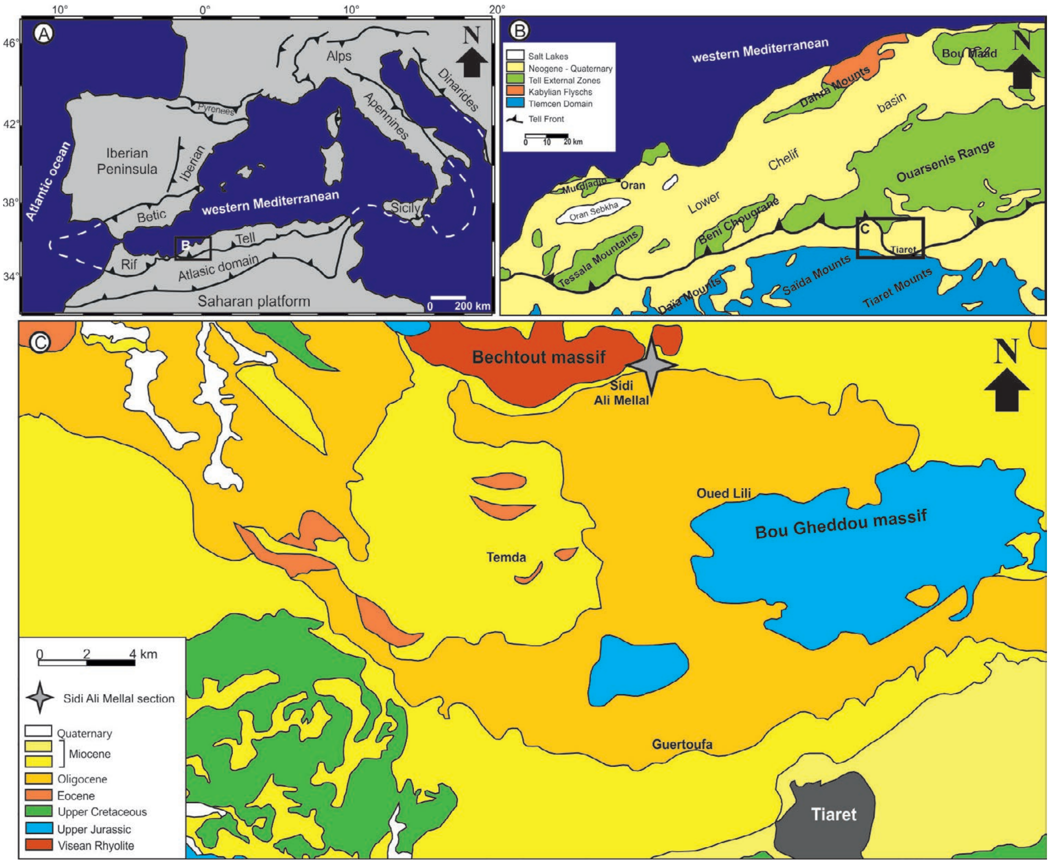

Figure 1. A) Location of Orania (Northern Algeria) in the Western Mediterranean. B) The main structural domains of Western Algeria. C) Geological map of the study area.

Table 1. Length, width and l/w ratio of the studied 65 *Cardioichnus planus* (in mm).

Sample	Length	Width	L/W Ratio
CAR-SAM-001	24	21	1.14
CAR-SAM-002	24	18	1.33
CAR-SAM-003	23	16	1.43
CAR-SAM-004	26	24	1.08
CAR-SAM-005	21	20	1.05
CAR-SAM-006	27	22	1.22
CAR-SAM-007	26	22	1.18
CAR-SAM-008	27	22	1.22
CAR-SAM-009	23	19	1.21
CAR-SAM-010	21	20	1.05
CAR-SAM-011	24	20	1.2
CAR-SAM-012	22	20	1.1
CAR-SAM-013	26	22	1.18
CAR-SAM-014	23	19	1.21
CAR-SAM-015	23	16	1.43
CAR-SAM-016	21	18	1.16
CAR-SAM-017	21	18	1.16
CAR-SAM-018	22	20	1.1
CAR-SAM-019	27	22	1.22
CAR-SAM-020	27	20	1.35
CAR-SAM-021	22	18	1.22
CAR-SAM-022	25	21	1.19
CAR-SAM-023	21	17	1.23
CAR-SAM-024	28	21	1.33
CAR-SAM-025	24	21	1.14
CAR-SAM-026	23	17	1.35
CAR-SAM-027	24	17	1.41
CAR-SAM-028	22	19	1.15
CAR-SAM-029	24	21	1.14
CAR-SAM-030	22	18	1.22
CAR-SAM-031	27	20	1.35
CAR-SAM-032	25	22	1.13
CAR-SAM-033	25	20	1.25
CAR-SAM-034	23	19	1.21
CAR-SAM-035	28	22	1.27
CAR-SAM-036	26	20	1.3
CAR-SAM-037	32	24	1.33
CAR-SAM-038	27	24	1.12
CAR-SAM-039	25	22	1.13
CAR-SAM-040	27	24	1.12
CAR-SAM-041	26	23	1.13
CAR-SAM-042	33	25	1.32
CAR-SAM-043	24	21	1.14
CAR-SAM-044	37	25	1.48
CAR-SAM-045	25	19	1.31
CAR-SAM-046	32	24	1.33
CAR-SAM-047	26	22	1.18
CAR-SAM-048	32	26	1.23
CAR-SAM-049	26	21	1.23
CAR-SAM-050	22	18	1.22
CAR-SAM-051	24	19	1.26
CAR-SAM-052	25	23	1.08
CAR-SAM-053	25	18	1.38
CAR-SAM-054	21	18	1.16
CAR-SAM-055	30	26	1.15
CAR-SAM-056	27	21	1.28
CAR-SAM-057	29	23	1.26
CAR-SAM-058	33	25	1.32
CAR-SAM-059	30	21	1.42
CAR-SAM-060	22	21	1.04
CAR-SAM-061	31	25	1.24
CAR-SAM-062	25	23	1.08
CAR-SAM-063	30	22	1.36
CAR-SAM-064	24	19	1.26
CAR-SAM-065	26	21	1.23
Average	25.58	20.87	1.22

3. MATERIAL AND METHODS

More than seventy specimens of *C. planus* have been observed and collected by the authors during several field trips in to the Tiaret basin between 2019 and 2020. The studied collection (*N* = 65) is deposited at the Laboratory of Geology of Sahara at Kasdi Merbah Ouargla University (CAR-SAM-001 to CAR-SAM-065). These sixty-five specimens were selected because of their preservation. They were photographed both in the field and the laboratory. The measurements were taken in the laboratory (Table 1). Also, the ichnotaxonomic identification of *C. planus* is in accordance with SMITH & CRIMES (1983).

4. RESULTS

4.1. Description

Cardioichnus planus is very abundant in the Sidi Ali Mellal section. It is a hypichnion in the sandstone beds, and co-occurs with *Scolicia vertebralis* (Fig. 2).

The studied traces (Fig. 3A-F) are heart-shaped mounds. They are ovoid or subquadratic in outline, bilobate and bilaterally symmetrical. Their two lateral lobes are generally rounded, curved, and merged at the central axial depressed V-shaped depression. Some specimens show a well developed posterior impression with a sharp edge at the terminus, which extends from the V-shaped depression, and separates the two distinct lobes. The mounds are 20–37 mm long and 16–26 mm wide, with a length/width ratio of about 1.05–1.42. The mean length (*N* = 65) is 25.58 mm, whereas the mean width is 20.87 mm (Table 1).

4.2. Remarks

The selected samples have been attributed to *Cardioichnus planus* due to their dimensions (l= 20–37 mm; w= 16–26 mm), and the length/width ratio which are similar to that described by SMITH & CRIMES (1983) and BRUSTUR (2005). The ovoid to subquadratic form of the studied specimens, their preservation as a convex body and the presence of two curved lateral lobes merged at the median longitudinal V-shaped depression and posterior impression characterize *C. planus* (SMITH & CRIMES, 1983; UCHMAN, 2007a), and confirm their determination as this ichnospecies.

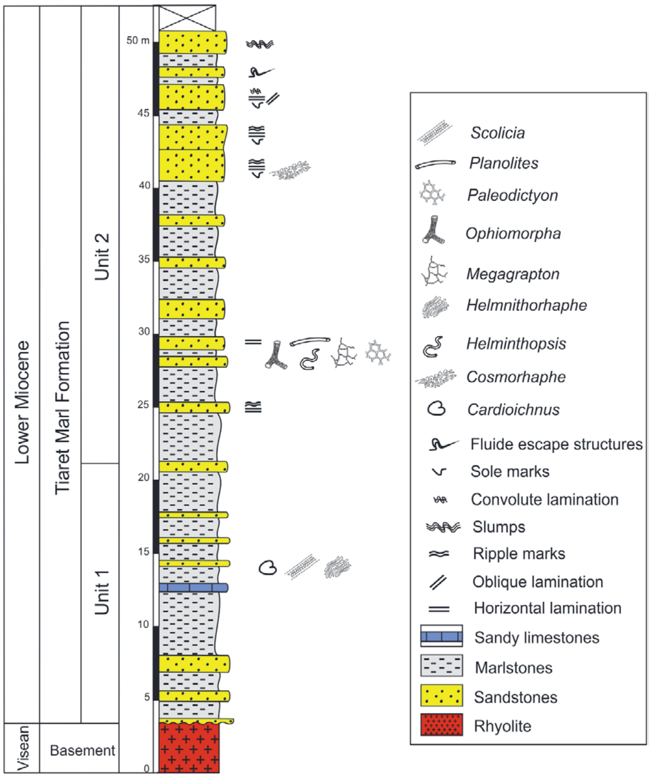

Figure 2. The stratigraphic succession and vertical distribution of trace fossils of the lower Miocene Tiaret Marls Formation in the Sidi Ali Mellal section.

Figure 3. *Cardioichnus planus* from the lower Miocene of the Sidi Ali Mellal section. A) CAR-SAM-043. B) CAR-SAM-044. C) CAR-SAM-063. D) CAR-SAM-055. E) CAR-SAM-056. F) CAR-SAM-057 (scale: 1 cm).

5. DISCUSSION

5.1. Probable local tracemakers of the Algerian *C. planus*

Spatangoid echinoderms or heart urchins are known from the early Jurassic (BUATOIS & MÁNGANO, 2018). They are the producers of *Bichordites*, *Cardioichnus* and *Scolicia*. *Bichordites* and *Scolicia* are attributed to the burrowing of spatangoids. *Scolicia* is the best known among these ichnogenera. Its oldest occurrence is from the Tithonian of Bulgaria (TCHOUMATCHENCO & UCHMAN, 2001).

All *Cardioichnus* ichnospecies are considered to be resting traces produced by spatangoid echinoids (SMITH & CRIMES, 1983; PLAZIAT & MAHMOUDI, 1988; MAYORAL & MUÑIZ, 2001; KAPPUS & LUCAS, 2019). The determination of tracemaker is problematic. In the Oligocene of Trentino (north-eastern Italy), *Cardioichnus* isp. and the associated *Bichordites* have been attributed to *Eupatagus ornatus* (BERNARDI et al., 2010). Furthermore, *Bichordites* recorded from the middle Miocene of Spain has been attributed to the grazing activity of spatangoid echinoids assigned to the genus *Maretia* (GIBERT & GOLDRING, 2008). Recently, the spatangoid *Heteraster* has been considered as the tracemaker of the ichnospecies *C. biloba*, described from the mid-Cretaceous of New Mexico in the United States of America (KAPPUS & LUCAS, 2019).

The studied outcrop belongs to the southern Tellian border of the Ouarsenis range which constitutes the northern edge of the Tiaret Miocene basin. The most important palaeontological in-

Figure 4. *Echinocardium nummuliticum* PÉRON & GAUTIER (1885) holotype, MNHN.F.J01420. Photography Peter Massicard, program RECOLNAT (ARN-11-INBS-0004). A) Aboral view. B) Oral view. C) Posterior view. D) Side view. E) Anterior view (scale: 0.5 cm).

vestigations which yielded a rich echinoid fauna in the southern border of the Ouarsenis range have been carried out at the Kef Ighoud section, located 50 km to the ENE of our study area. Kef Ighoud echinoid-rich deposits have been attributed to the Eocene (POMEL, 1885), the Oligocene (DALLONI, 1936; MATTAUER, 1958) and finally to the lower to middle Miocene on the basis of their planktonic foraminifera (DERKAOUI, 2017).

Several spatangoid echinoids have been described from the lower-middle Miocene of the Kef Ighoud section (COTTEAU et al., 1885; POMEL, 1885). The most important ones are *Echinocardium dubium* PÉRON & GAUTHIER, 1885; *E. nummuliticum* PÉRON & GAUTHIER (Fig. 4), 1885; *Euspatangus cruciatus* PÉRON & GAUTHIER, 1885; *E. hangenmulleri* PÉRON & GAUTHIER, 1885; *E. subrostratus* PÉRON & GAUTHIER, 1885; *Pericosmus nicaisei* POMEL, 1885; *P. subæquipetalus* POMEL, 1885; *Sarsella mauritanica* POMEL, 1885; *Schizaster mac carthyi* POMEL, 1885; *Spatanus* (*Pseudopatagus*) *cruciatus* POMEL, 1885 and *Tuberaster tuberculatus* PÉRON & GAUTHIER, 1885. Some taxa such as *S. mauritanica* and *T. tuberculatus* have been placed into the spatangoid genus *Hemipatagus* (KROH, 2007). This echinoid fauna is important due to its endemism, and has never been reported out of this area.

Probable producers of *Cardioichnus* are proposed on the basis of the similarities in size and morphology between the spatangoids and *Cardioichnus* (KAPPUS & LUCAS, 2019). However, among the spatangoid assemblage of Kef Ighoud, three species have similar sizes to the studied *Cardioichnus* specimens. They include *Echinocardium dubium* (l= 26 mm; w= 25 mm), *E. nummuliticum* (l= 26 mm; w= 23 mm) and *Euspatangus hangenmulleri* (l= 25; w= 25). According to the l/w ratio, the two *Echinocardium* species resemble *Cardioichnus planus*. However, the morphology of *Echinocardium nummuliticum* allows proposing it as the probable tracemaker (Fig. 4). The size decreases near the posterior part of the test where a prominent rostrum is present. Accordingly, the posterior impression at the terminus of the trace could be interpreted as the imprint of this rostrum. Alternatively, the ambitus of this species is heart-shaped, whereas it is rounded in *E. dubium*. This confirms that *C. planus* most closely resembles *E. nummuliticum* in size and morphology.

Echinocardium species occur generally in shallower environments. POMEL (1887) indicated that the attribution of *E. nummuliticum* to this genus by PÉRON & GAUTHIER is incorrect, and these specimens should be revised. However, it co-occurs with other sea urchins such as *Schizaster* (POMEL, 1885)

Table 2. Stratigraphic and geographic record of the ichnogenus *Cardioichnus*.

Age	Ichnotaxa	Country	References
Upper Jurassic	*Cardioichnus* isp.	Algeria	BOUCHEMLA et al. (2020)
Lower Cretaceous	*Cardioichnus* isp.	Spain	MONACO et al. (2005); GIANNETTI et al. (2014)
	C. biloba	United States of America	KAPPUS & LUCAS (2019, 2020)
	C. foradadensis	United States of America	KAPPUS & LUCAS (2020)
Upper Cretaceous	*C. planus*	Poland	SMITH & CRIMES (1983)
	C. planus	Spain	SMITH & CRIMES (1983)
	C. planus	Italy	UCHMAN (2007a)
	Cardioichnus isp.	Poland	KSIĄŻKIEWICZ (1977); RAJCHEL & UCHMAN (2012)
	Cardioichnus isp.	Iran	BAYET-GOLL et al. (2016)
Paleocene	*Cardioichnus* isp.	Italy	UCHMAN (2007b)
Eocene	*C. ovalis*	Switzerland	SMITH & CRIMES (1983)
	C. foradadensis	Spain	PLAZIAT & MAHMOUDI (1988)
	C. ovalis	Romania	BRUSTUR (1996)
	C. cf. *planus*	Romania	BRUSTUR (1996)
	Cardioichnus isp.	Romania	BUATOIS et al. (2001)
	Cardioichnus isp.	Argentina	LÓPEZ-CABRERA et al. (2008)
	Cardioichnus isp.	Italy	MONACO et al. (2017)
Oligocene	*Cardioichnus* isp.	Italy	BERNARDI et al. (2010)
Oligocene/Miocene	*C. planus*	Romania	BRUSTUR (2005)
	Cardioichnus isp.	Tunisia	RIAHI et al. (2014)
Miocene	*Cardioichnus* isp.	New Zealand	MANLEY & LEWIS (1998)
	C. reniformis	Spain	MAYORAL & MUÑIZ (2001)
	C. planus	Spain	MAYORAL & MUÑIZ (2001)
	Cardioichnus isp.	Spain	MAYORAL & MUÑIZ (2001)
	Cardioichnus isp.	Spain	GIBERT & ROBLES (2005)
	Cardioichnus isp.	Argentina	LÓPEZ-CABRERA et al. (2008)
	Cardioichnus isp.	Algeria	CHERIF et al. (2020)
	Cardioichnus planus	Algeria	This paper
Pliocene	*Cardioichnus* isp.	Spain	GIBERT & MARTINELL (1995)
	C. planus	Spain	GIBERT & MARTINELL (1999)
Pleistocene	*Cardioichnus* isp.	Cape Verde	MAYORAL et al. (2013)
	Cardioichnus isp.	Italy	CARUSO & MONACO (2015)

which could be found in deep basins (MCKINNEY, 1986). Also, echinoids of the *Echinocardium* group are responsible for traces with one drain such as *Bichordites*, which could be continuous with *Cardioichnus* and produced by the same organism. *Bichordites* occurs from shallow-marine settings (UCHMAN & KRENMAYR, 1995; BERNARDI et al., 2010; CARUSO & MONACO, 2015) to slope deposits in soft substrates (VILLEGAS-MARTÍN et al., 2014).

5.2. Stratigraphy, palaeoenvironments and palaeogeography

The oldest *Cardioichnus* were observed in the Kimmeridgian of northwestern Algeria, near this study area (BOUCHEMLA et al., 2020) (Table 2). It occurs in the lower to transitional offshore environment characterizing the archetypal *Cruziana* ichnofacies. This area belongs to the south Tethyan Ocean. This constitutes the only record of this ichnogenus in the Jurassic. In the lower Cretaceous, *Cardioichnus* occurred in similar environments to those of the upper Jurassic of Algeria. It has been reported in several domains from Spain (Tethyan Realm) (MONACO et al., 2005; GIANNETTI et al., 2014) to North America (KAPPUS & LUCAS, 2019, 2020). *Cardioichnus* is common in flysch deposits from as early as the upper Cretaceous. It has been found in Iran, Italy, Poland and Spain (KSIĄŻKIEWICZ, 1977; SMITH & CRIMES, 1983; UCHMAN, 2007a; RAJCHEL & UCHMAN, 2012; BAYET-GOLL et al., 2016). The Cenozoic records seem to be more numerous. This ichnogenus is known from the Palaeocene siliciclastic flysch deposits of Italy (UCHMAN, 2007b). It had a larger distribution during the Eocene, generally in the circum-Tethyan region (SMITH & CRIMES, 1983; PLAZIAT & MAHMOUDI, 1988; BRUSTUR, 1996; BUATOIS et al., 2001; MONACO et al., 2017) and South American (LÓPEZ-CABRERA et al., 2008) deep-sea systems, within ichnoassemblages assigned to the *Zoophycos* and *Nereites* ichnofacies. *Cardioichnus* also has been reported from the Oligocene and the Oligo-Miocene of the Mediterranean Tethys in shallow (BERNARDI et al., 2010) to deep-sea deposits (BRUSTUR, 2005; RIAHI et al., 2014). Miocene records of *Cardioichnus* are widespread, e.g., it occurs in New Zealand (MANLEY & LEWIS, 1998), Argentina (LÓPEZ-CABRERA et al., 2008), and the western Mediterranean basin, especially in Spain (MAYORAL & MUÑIZ, 2001; GIBERT & ROBLES, 2005) and Algeria (CHERIF et al., 2021; this paper). Miocene *Cardioichnus* have been reported from infralittoral shelf sands to deep-sea deposits. In the Pliocene, *Cardioichnus* is known only in Spain from sandy storm beds, typical of the *Cruziana* ichnofacies (GIBERT & MARTINELL, 1995, 1999). Finally, the newest records of this trace fossil are from the Pleistocene of the Tropical Eastern Atlantic (Cape Verde), in a moderate to high-energy shallow marine environment, where it constitutes part of the proximal *Cruziana* ichnosubfacies (MAYORAL et al., 2013), and from the shallow deposits of southern Italy (CARUSO & MONACO, 2015).

6. CONCLUSIONS

The studied samples allow the following conclusions to be drawn:

Abundant *Cardioichnus planus* has been found for the first time in Africa;

The studied specimens are dated as being of the lower Miocene age, and co-occur with *Scolicia vertebralis*;

The endemic spatangoid echinoderm *Echinocardium nummuliticum* PÉRON & GAUTHIER, 1885 represents the probable tracemaker of the studied *C. planus*.

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