Estonian Journal of Earth Sciences, 2017, **66**, 3, 174–182 https://doi.org/10.3176/earth.2017.13

First description of *Skolithos* burrows from the Cambrian–Ordovician boundary interval of the Central Anti-Atlas, Morocco

Abdelfattah Azizi[a], Olev Vinn[b], Khadija El Hariri[a], Ahmid Hafid[a] and Khaoula Kouraiss[a]

[a] Département des Sciences de la Terre, Faculté des Sciences et Techniques-Guéliz, Université Cadi Ayyad, avenue Abdelkrim El Khattabi, BP 549, 40000 Marrakesh, Morocco; abdelfattah.azizi@edu.uca.ac.ma
[b] Department of Geology, University of Tartu, Ravila 14A, 50411 Tartu, Estonia; Olev.Vinn@ut.ee

Received 14 February 2017, accepted 6 June 2017, available online 6 July 2017

Abstract. *Skolithos* burrows indicate high-energy nearshore environment. In this paper, abundant *Scolithos* burrows from two particular levels of the Cambrian–Ordovician boundary interval of the Central Anti-Atlas, Morocco, are described for the first time. The first level occurs at the boundary between the Azlag Formation and Jbel Lmgaysmat Formation (Furongian), where the burrows are 5–80 cm long and 3–7 mm wide, straight to slightly curved, with mostly circular, but sometimes also oval apertures. The second level occurs within the unconformity underlining the Tremadocian cycle (Fezouata Shale). The burrows of *Skolithos linearis* associated with that level are straight to slightly curved, 2–15 cm long and 2–4 mm wide. The absence of encrustation above the burrowed beds indicates that these traces were made in a soft sediment.

Key words: trace fossils, bioturbation, *Skolithos*, pipe-rocks, sedimentary facies, Cambrian, Ordovician.

INTRODUCTION

Abundant vertical burrows in *Skolithos* ichnofacies are commonly called ‘pipe-rock’. The term was used for the first time to describe the highly to moderately bioturbated sandstones with vertical burrows in the lower Cambrian Eriboll Sandstone in Scotland (Peach & Horne 1884). The *Skolithos* burrows are among the best described trace fossils of Palaeozoic strata. They first appear in the early Cambrian and abruptly increase in abundance towards the end of the early Cambrian. The Cambrian is characterized by an exceptional rise in the density and depth of bioturbation. However, many workers argue that Cambrian and lower Palaeozoic levels of bioturbation remained low compared to younger times (Tarhan et al. 2015). This biological event is related to the rapid appearance of various metazoans. Droser (1991) showed that the abundance of *Skolithos* pipe-rocks decreased after the Cambrian as a result of physical and biological factors associated with the Great Ordovician Biodiversification Event. After the Palaeozoic, the *Skolithos* ichnofacies was dominated by *Ophiomorpha* and rare *Skolithos* pipe-rocks.

The *Skolithos* ichnofacies has been found in many localities around the world, within various depositional environments such as estuary mouth (Hiscott et al. 1984; Mángano et al. 1996), shoreface shelf (Hallam & Swett 1966; McKie 1990; Prave 1991; Simpson et al. 2002; McIlroy & Garton 2004; Davies et al. 2009) shoreface–intertidal zone (Simpson & Eriksson 1990; Simpson 1991) and intertidal–subtidal zone (Goodwin & Anderson 1974; Baldwin 1977; Driese et al. 1980; Cornish 1986; Bjerstedt & Erickson 1989). It occurred also in non-marine environments (Fitzgerald & Barrett 1986).

The *Skolithos* ichnofacies has most often been identified in the early Cambrian (Goodwin & Anderson 1974; Driese et al.1980; Droser 1991; Prave 1991; Simpson 1991). It is dominated by *Skolithos linearis* and *Monocraterion*. The best-known and -studied example is the Eriboll Sandstone Formation in Scotland (Hallam & Swett 1966; McKie 1990; Simpson et al. 2002; McIlroy & Garton 2004; Davies et al. 2009). The *Skolithos* ichnofacies occurs also in the middle Cambrian of northwestern Argentina containing various ichnofauna (Mángano & Buatois 2004): *Skolithos linearis*, *Diplocraterion parallelum*, *Syringomorpha nilssoni*, *Syringomorpha* sp. and *Arenocolites* sp. This ichnofacies has also been identified from rocks at the Cambrian–Ordovician boundary, in the Furongian–Tremadocian succession of New Mexico (Chafetz et al. 1986) and

Cabos Series, Northern Spain (Baldwin 1977). Both examples contain very abundant *Skolithos linearis* ichnofauna.

The Cambrian–Ordovician boundary interval in the Central Anti-Atlas (Morocco) comprises the Jbel Lmgaysmat Formation (Tabanit Group) and the base of the Lower Fezouata Formation (Feijas Externes Group). During the late Cambrian and Early Ordovician the Central Anti-Atlas was a part of the northern margin of the large continent of Gondwana. The Furongian–Tremadocian succession of this area is dominated by siliciclastic rocks such as sandstones and siltstones, which show two levels of *Skolithos* pipe-rock. This paper will focus on (1) studying the morphological characteristics of *Skolithos* pipe-rocks in detail and (2) analysing the palaeoenvironment and palaeoecology of the trace maker.

GEOGRAPHIC LOCATION AND STRATIGRAPHY

The Cambrian succession of Morocco overlies the Precambrian Panafrican orogen in the Anti-Atlas belt and High-Atlas Mountain (Destombes et al. 1985). The integral Cambrian succession crops out in the Central Anti-Atlas, essentially in the Foum Zguid area located in mid-Morocco, in the southern slope of the Central Anti-Atlas Mountains (Fig. 1). The lithostratigraphic syntheses of the Cambrian of the Anti-Atlas Mountains have been provided essentially by Destombes et al. (1985), Destombes & Feist (1987) and Destombes (1989), but little attention has been paid to ichnology. The stratigraphic succession of the Cambrian in this area is subdivided into four groups: the Taroudant, Tata, Feijas Internes and Tabanit groups, dominated by siliciclastic sediments, overlain by the transgressive Ordovician Fezouata Shale (Feijas Externes Group). Herein our study focuses on the topmost lithostratigraphic unit of the Tabanit Group represented by the Jbel Lmgaysmat Formation (Destombes et al. 1985), which crops out exclusively in this area; its limited geographic extent may be related to the erosive unconformity that covers the unit. Two detailed sections were studied from the Jbel Lmgysmat Formation (Jbel Lbhibha and Aghlan), and one other detailed section from the Cambrian–Ordovician transition (Alougoum section) (Fig. 2).

The marine sedimentation of the Jbel Lamgaysmat Formation (Fig. 3) corresponds to two depositional transgressive–regressive parasequences, which allow the subdivision of this formation into two members. They are 15–20 m thick and consist mainly of shales with some calcareous layers and fine- to medium-grained sandstones. The base of the Jbel Lmgaysmat Formation is underlined by an erosive discontinuity marked by conglomeratic to coarse-grained sandstones rich in rhyolitic gravels (Destombes et al. 1985; Destombes 1989).

SKOLITHOS ICHNOFABRIC

Burrows occur in two particular horizons at the base of the Jbel Lmgaysmat Formation and at the base of the Lower Fezouata Formation (Figs 4, 5).

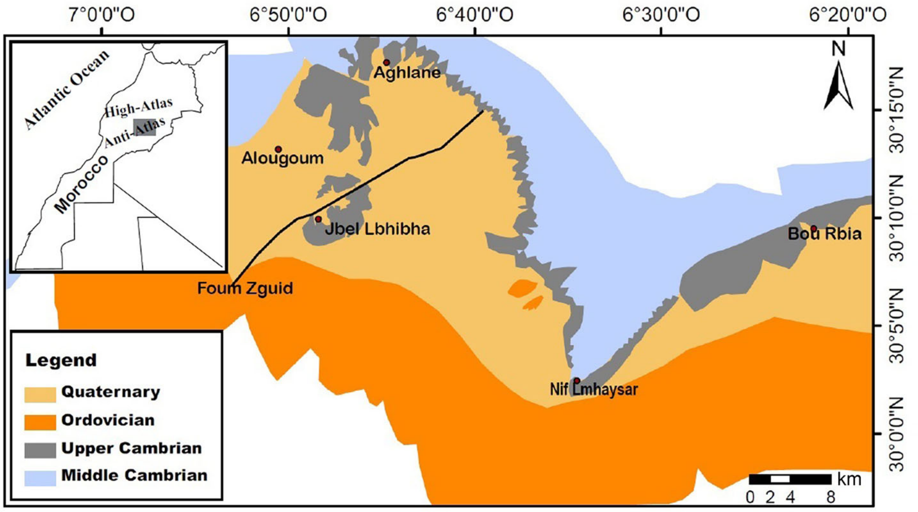

Fig. 1. Geological and location map of studied outcrops in the Foum Zguid syncline area, in the south slope of the central Anti-Atlas Mountains. After Destombes (1989).

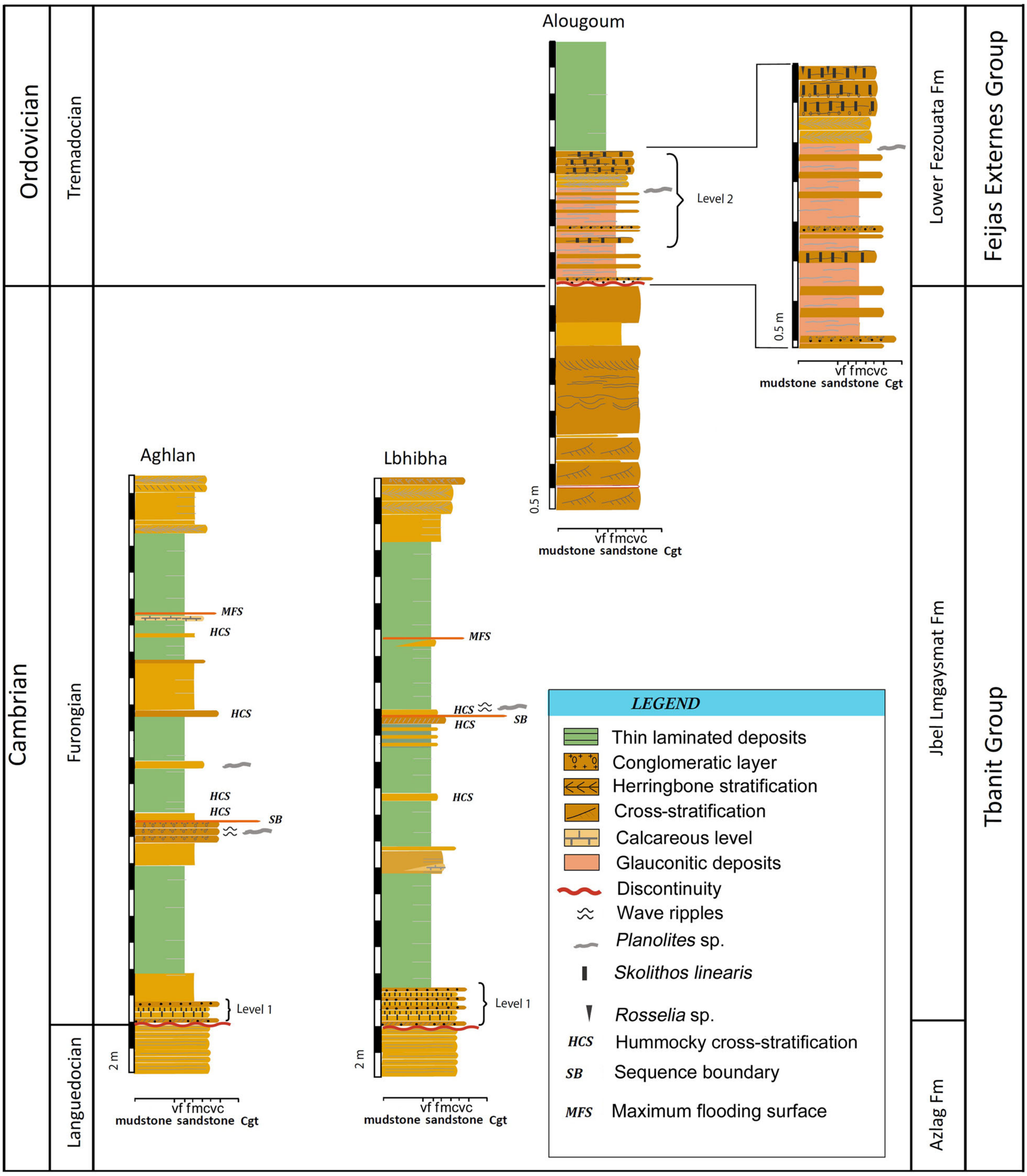

Fig. 2. Stratigraphical sections studied in the Foum Zguid area: Aghlan (30°18′13″N, 6°44′47″W), Jbel Lbhibha (30°09′51″N, 6°48′05″W) and the Cambrian–Ordovician transition in the Alougoum section (30°16′08″N, 6°51′06″W). Cgt, Conglomerate; f, fine-(grained sandstone); vf, very fine; m, medium; c, coarse; vc, very coarse. Modified after Destombes (1989).

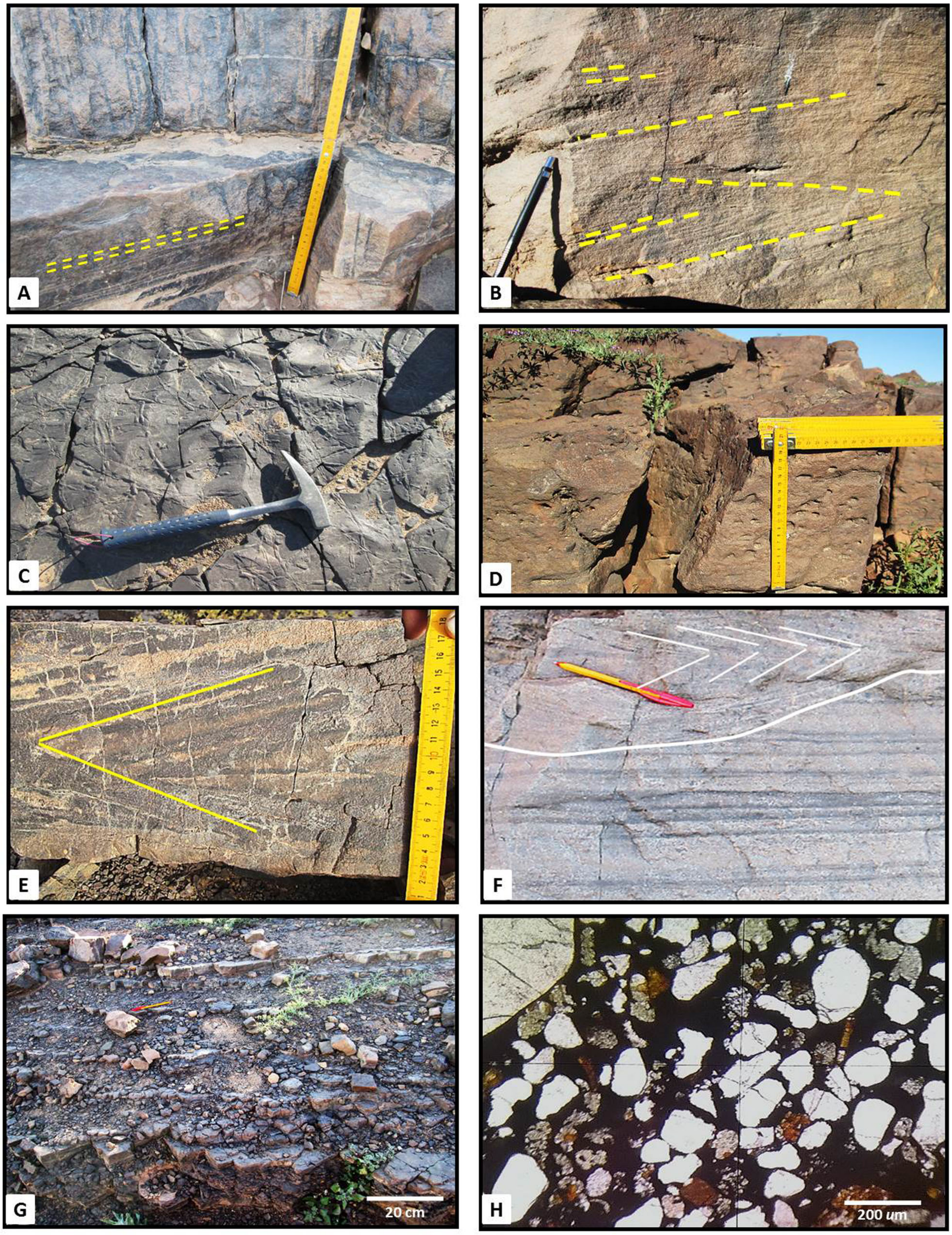

Fig. 3. Sedimentary facies of the Cambrian–Ordovician boundary. **A**, planar to low-angle cross-stratified coarse-grained sandstone with *Skolithos linearis* burrows. **B**, coarse-grained cross-stratified sandstone. **C**, polygonal and wavy ripple textures bioturbated by *Planolites montanus*. **D**, clay pebbles in coarse-grained sandstone. **E**, herringbone stratifications in medium-grained sandstone. **F**, planar coarse-grained sandstone and herringbone stratifications separated by an erosion surface. **G**, ferruginous condensed beds from the Cambrian–Ordovician unconformity. **H**, thin section in the glauconitic ferruginous sandstone.

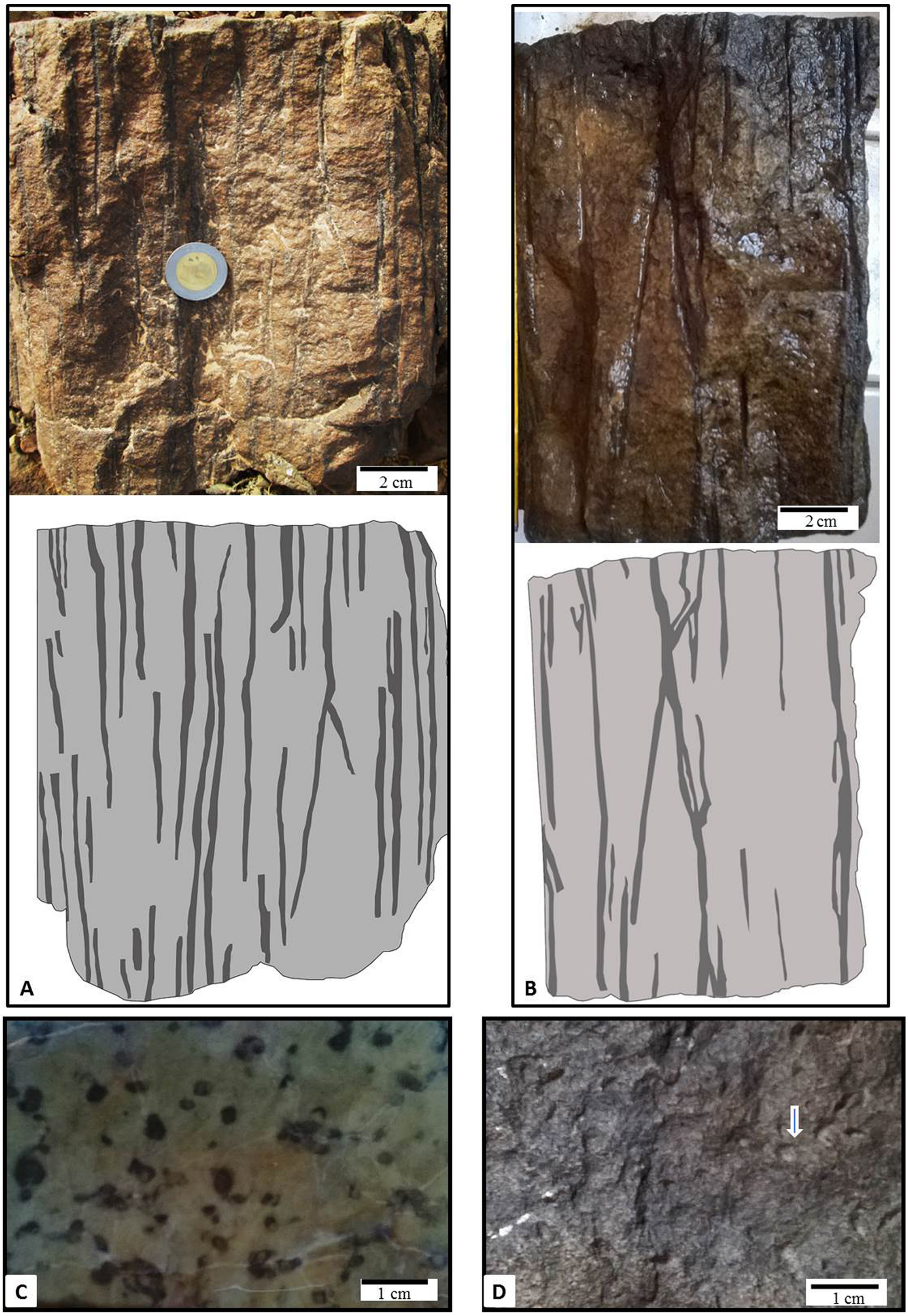

Fig. 4. *Skolithos* ichnofabric. **A**, longitudinal section of abundant *Skolithos linearis* in the medium- to coarse-grained sandstone from the ferruginous facies in the contact between the Lower Fezouta and Jbel Lmgaysmat formations. **B**, longitudinal section of *Skolithos linearis* in the coarse-grained planar cross-stratified sandstone with numerous erosion surfaces. **C**, horizontal polished section of *Skolithos linearis*. **D**, apertures of *Skolithos* burrows on the surface of the bed.

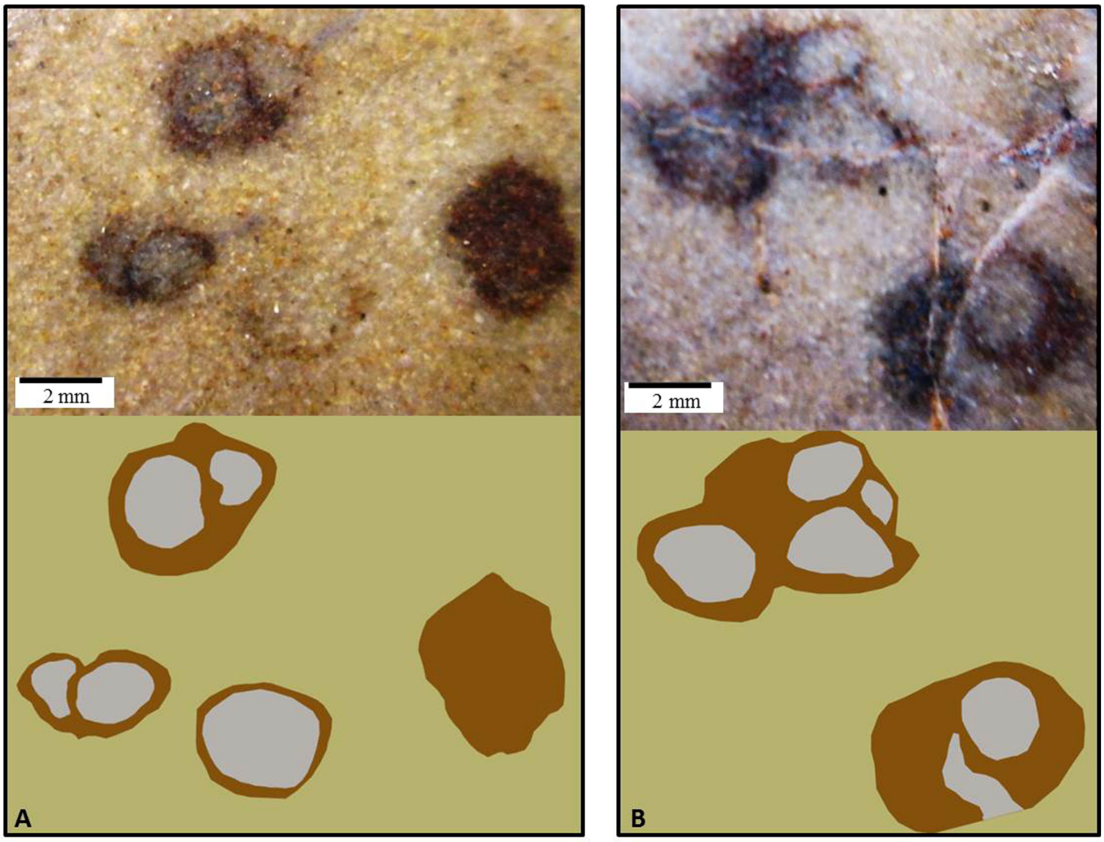

Fig. 5. Polished cross sections showing the details of internal structures of burrows filled by mud (brown colour). Each burrow contains one or several secondary tubes filled by quartz (grey colour).

The first level consists of 10–90 cm thick medium- to coarse-grained micaceous sandstone beds, separated by erosion surfaces and fully bioturbated by vertical to steeply inclined 5–80 cm long tubes. The bioturbation index varies between 1 and 2 (*sensu* Taylor & Goldring 1993), increasing mainly from base to top of the lower horizon of the Jbel Lmgaysmat Formation. We rarely find some tubes intersecting others (Fig. 4). The burrows are mostly cylindrical but some from the topmost part of the bed were funnel-shaped. The burrow apertures at the bedding plane surface are usually circular but some apertures are slightly oval, possibly due to sediment compaction. The burrows are mostly 4–5 mm wide, with a maximum diameter between 1 and 9 mm (Fig. 6).

The polished cross sections prepared in the laboratory show that the shape of the transversal section of burrows is usually circular to slightly oval. The maximum diameter collected from 100 tubes in 105 cm^2 varies between 1 and 7 mm, whereas burrows with diameters of 2 and 3 mm dominate (Fig. 7). The boundary between the burrows and the host rock is clearly visible because of different lithologies. The burrows are filled with mud

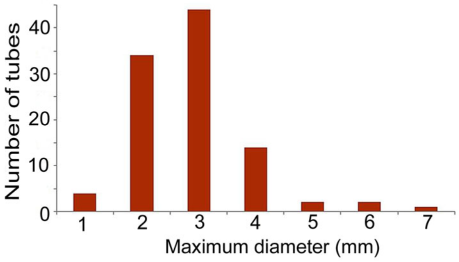

Fig. 6. Distribution of the maximum diameter of 100 tubes measured in 110 cm^2 on the polished cross section.

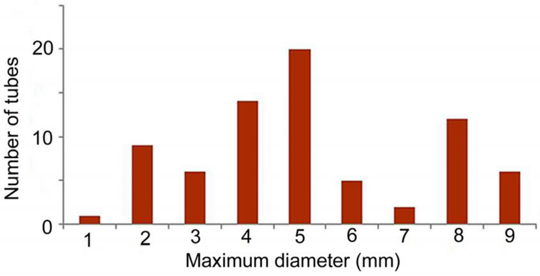

Fig. 7. Distribution of the maximum diameter of 72 tubes measured in 105 cm^2 on the bedding plane surface.

rich in iron oxides which give it the brown colour. The sand grains in the surrounding sediment are formed mainly of quartz and mica flakes. There is no concentric lamination in the infilling of burrows, however, each one contains one or several tubes that are termed as secondary tubes here. Their diameter varies between 1 and 2 mm, and they are filled mainly by quartz grains (Fig. 5).

DISCUSSION

The burrows of the Jbel Lmgaysmat Formation in the Central Anti-Atlas of Morocco show the same characteristics of *Skolithos linearis* as described by Haldeman (1840) and later authors (Desjardins et al. 2010). The nature and the ecology of the trace makers are still not known. The elongated vertical shape and the circular section of burrows may be made by worm-like organisms, most likely by some polychaetes. However, some arthropods are also capable of producing cylindrical burrows. A burrowing nereidid polychaete *Alitta virens* (Sars) usually produces burrows similar to those of *Arenicolites* and *Skolithos* (Herringshaw et al. 2010). The studied *Skolithos* burrows are similar to vertical burrows made during the pioneer digging behaviour of *Alitta virens*. As a result of an experimental study, Herringshaw et al. (2010) found that within 24 h of settlement, *Alitta virens* made numerous vertical burrows penetrating the full depth of sediment in the tank. Thus, it is possible that the studied *Skolithos* burrows may represent a similar behaviour in a freshly deposited bed of sand. *Skolithos* burrows have usually been interpreted as domichnia, based on modern analogues (Seilacher 1967; Pemberton & Jones 1988; Vossler & Pemberton 1989). The studied *Skolithos* burrows are presumably domichnia of a suspension-feeding animal that excavated a burrow for hiding from predators and for gaining an upright position on the sediment–water interface. The upright position was favourable for the animal as it enabled the animal to best filter out food particles from the water column. The relatively high density of *Skolithos* burrows in the studied beds presumably indicates that trace makers did not have large crowns for filter feeding or all burrows were not populated by living animals at the same time. The presence of secondary tubes in one bed presumably resulted from a small change or correction of the position of the animal during its life. Most likely the trace maker was capable of changing its position laterally, without leaving the burrow. It is less likely that the same burrow was inhabited by more than one suspension-feeding animal at the same time as they would have interfered with each other's feeding and made it less efficient.

The oval shape of some apertures may be due to sediment compaction. Digging long burrows that reach 80 cm was possible in medium-grained sand rich in mica flakes. The length of the burrowing animals cannot be deduced from the burrow morphology as animals with very different length can produce burrows of a similar diameter. However, the burrowing animals were likely able to completely retract into the burrow, so their maximal length was likely less than 80 cm. The significant proportion of high diameter apertures from the surface of the bed may be a result of the slightly funnel shape of the topmost part of some burrows. The funnel shape of the aperture may have resulted from the back- and forward movement of the worm-like organisms inhabiting the burrows. However, the rotating of the worm in its burrow would also produce a funnel-shaped aperture.

The studied *Skolithos* diameters vary, indicating that animals of various growth stages produced the burrows. The distribution of diameters in the burrows of level one (Fig. 6) are more consistent with the normal population of animals of the same species. The younger growth stages dominate the population (Fig. 6) and only few animals in the population achieved the maximal size. The distribution of burrow diameters in level two shows a somewhat more complex pattern (Fig. 7). There are several maxima on the graph which could indicate that more than one species produced these burrows. Three maxima could indicate that at least three morphologically distinct species were involved in trace making. More than one species with similar life mode could co-exist without excessive competition if their niches were somewhat different. For example, they may have fed on different-sized food particles. Alternatively, different species did not populate the burrows at the same time and the *Skolithos* pipe-rock may represent a result of burrowing by temporarily successive populations.

CONCLUSIONS

Two horizons with *Skolithos* have been recognized at the base of the Jbel Lmgaysmat Formation and a single horizon is found at the base of the Lower Fezouata Formation. The burrows of the Jbel Lmgaysmat Formation in the Central Anti-Atlas of Morocco are similar to *Skolithos linearis* Haldeman, 1840. The *Skolithos* burrows in the Jbel Lmgaysmat and Lower Fezouata formations were made by worm-like organisms, most likely by some polychaetes. The high density of *Skolithos* burrows in the studied beds presumably indicates that trace makers did not have large crowns for filter feeding or all burrows were not populated by living animals at the same time. Several maxima on the graph of burrow diameters could indicate that more than one species produced these burrows. Based on analogy with modern polychaete *Alitta virens*, it is possible that the studied *Skolithos* burrows were made in a freshly deposited bed of sand during a relatively short period of time.

Acknowledgements. Financial support to O. V. was provided by the Estonian Research Council project IUT20-34 'The Phanerozoic journey of Baltica: sedimentary, geochemical and biotic signatures of changing environment – PalaeoBaltica'. This paper is a contribution to IGCP 653 'The onset of the Great Ordovician Biodiversification Event'. Abderrazzak Amzil, Mohammed Morabit and Youness Tamraoui are thanked for their assistance in the field. We are grateful to the reviewers Andrei Dronov and Sören Jensen for their constructive comments. The publication costs of this article were covered by the Estonian Academy of Sciences.

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Maroko Anti-Atlase Kambriumi–Ordoviitsiumi piirikihtides esinevate *Skolithos*'e käikude esmakirjeldus

Abdelfattah Azizi, Olev Vinn, Khadija El Hariri, Ahmid Hafid ja Khaoula Kouraiss

Skolithos'e käigud on iseloomulikud liikuvaveelisele kaldalähedasele keskkonnale. *Skolithos*'e käigud esinevad arvukalt kahel tasandil. Esimene on seotud Azlagi kihistu ja Jbel Lmgaysmati kihistu (Furong) vahelise piiriga. Esimesel tasandil esinevad *Skolithos*'e käigud on 5–80 cm sügavused ja ümarate suudmetega. Teise käikudega tasandi peal algab Tremadoki tsükkel. Teisel tasandil esinevad *Skolithos*'e käigud on 2–15 cm sügavused ja 2–4 mm läbimõõduga. Inkrusteeriva fauna puudumine *Skolithos*'e käikudega kihtide peal näitab, et käigud on kaevatud pehmesse settesse.