

Supplementary File 2 for Uchman A., Hanken N.-M., Nielsen J.P., Grundvåg S.-A. & Piasecki S. 2016. Depositional environment, ichnological features and oxygenation of Permian to earliest Triassic marine sediments in central Spitsbergen, Svalbard. *Polar Research* 35. Correspondence: Alfred Uchman, Jagiellonian University, Institute of Geological Sciences, Oleandry Str. 2a, PL-30-063, Kraków, Poland. E-mail: alfred.uchman@uj.edu.pl

Systematic description of burrows

Some of the illustrated specimens are housed in the Institute of Geological Sciences of the Jagiellonian University, Poland, with collection prefix INGUIJ207P. Material housed at Tromsø University Museum, University of Tromsø, Norway, has collection prefix TSGF. The illustrated specimens seen in the field but not collected have not been allocated numbers.

The cited figures refers to the main text.

Arenicolites Salter, 1857

Arenicolites isp.

Figs. 5a, b, 11a?

Description. Simple, lined or unlined tubular structures, 3–6 mm in diameter, which are sub-vertical in the upper part and bent to inclined in the lower part, or rarely forming more complete U-shaped structures which are up to 110 mm wide. They occur in the upper part of sandstones, up to 90–220 mm below the top. They are filled with sandy or muddy sediment. Sand-filled specimens display dark muddy linings.

Remarks. The curvatures at terminations suggest a U-shaped, simple trace fossil such as *Arenicolites*. One specimen contained a full U-shaped burrow (Fig. 5b).

Arenicolites Salter is a dwelling and feeding burrow produced by suspension feeders, probably small crustaceans (Goldring 1962) or annelids (e.g., Hakes 1976). It occurs mostly in shallow-marine sediments (Crimes et al. 1977), especially in storm beds (Frey & Goldring 1992), but may occur in different full marine and brackish environments.

Chondrites Sternberg, 1833

Chondrites isp.

Fig. 5c

Description. Straight to slightly bent, branched tubular structures, 3–4 mm wide, continuing for at least 80 mm, filled with lighter material. Mostly first-order branches are present, with second-order branches occurring rarely. Branches have acute angles.

Remarks. *Chondrites* is a feeding system of unknown tracemakers, attributed to infaunal deposit feeders (e.g., Osgood 1970). According to Seilacher (1990) and Fu (1991), the tracemaker of *Chondrites* may have been able to live in dysaerobic conditions as a chemosymbiotic organism. A more detailed discussion of ichnogenus *Chondrites* is given by Fu (1991) and Uchman (1999).

Cylindrichnus Toots in Howard, 1966

cf. *Cylindrichnus* isp.

Figs. 5d, e, 7c

Description. Cf. *Cylindrichnus* isp. consists of two to three sub-vertical, slightly winding, overlapping tubes with thick walls. The tube is 6–9 mm in diameter, and its walls are about 2 mm thick. The walls show indistinct layering. The infilling is massive or shows shallow, irregular, poorly expressed menisci. In vertical cross-section, it can be seen as concentric structures, 15–21 mm thick. They are commonly attached to *Zoophycos* spreite.

Remarks. The common association with *Zoophycos* suggests that this trace fossil could be a part of the *Zoophycos* burrow system. However, this requires further research to clarify. *Cylindrichnus* is a poorly understood trace fossil with basic taxonomic problems needing a revision (Uchman & Krenmayr 1995) but lately, the type material of the type ichnospecies *C. concentricus* Toots in Howard (1966) was revised; it appeared that this a wide U-shaped burrow with concentric filling (Ekdale & Harding 2015).

Helminthopsis Wetzel & Bromley, 1996

Helminthopsis isp.

Fig. 6a, b

Description. Horizontal, loosely meandering, tubular trace fossil, about 10 mm wide. The meanders are 150–200 mm wide, with an amplitude of 70–80 mm.

Remarks. *Helminthopsis* is a eurybathic, facies-crossing trace fossil, common in flysch, and probably produced by polychaetes or priapulids (Książkiewicz 1977; Fillion & Pickerill 1990; Han & Pickerill 1995; Wetzel & Bromley 1996).

Macaronichnus Clifton & Thompson, 1978

Macaronichnus segregatis Clifton & Thompson, 1978

Fig. 5f–h

Description. Winding, horizontal cylinders preserved in full relief, 2.5–4 mm in diameter, composed of a core surrounded by a mantle. The sediment of the core is lacking heavy minerals other than black grains and mica flakes, which are common in the mantle and scattered in the host rock. Therefore, the core is lighter than the host rock. The trace fossil occurs gregariously in patches in thin layers.

Remarks. *Macaronichnus segregatis* is produced by small invertebrates feeding on epigranular microbial films, foremost within well-oxygenated foreshore sands at the depths 1.5–20 cm (Clifton & Thompson 1978; Saunders & Pemberton 1990; Pemberton et al. 2001). Recent *Macaronichnus segregatis* is produced by the opheliid polychaete *Euzonus*, mostly in foreshore but also in shoreface zones (Saunders 1989; Pemberton et al. 2001: 126) and *Euzonus* isp. (Gingras et al. 2002; Nara & Seike 2004).

Nereites MacLeay, 1839

Nereites missouriensis (Weller, 1889)

Figs. 7a–f, 8f, 11a–d

Description. Irregularly winding endichnial tubular structures, comprising a 2–3.5 mm, rarely up to 4.5 mm wide, dark-filled internal zone, surrounded by 1–3 mm wide, light-filled envelope, or ribbon structure, up to 9 mm wide, composed of crescent-shaped, irregular menisci. The menisci are strongly concave, with pointed terminations. They are filled with alternating darker and lighter material. Locally, the ribbons are rimmed by an indistinct, 2 mm thick, halo-like zone of slightly different colour. In some places, the ribbon is twisted and the

menisci coalesce, forming small feather-like structures. Some of the meniscate forms show slight plastic deformations. All these morphological types show intergradations.

Remarks. This trace fossil is very similar to *Scalarituba* Weller, which was included in *Nereites* (see Uchman 1995). The halo represents the reworked zone and the ribbon is the faecal strings. The tubular forms are less compacted than the ribbon forms. They were probably produced deeper in the sediment, which was already less saturated with water and less compacted, or the tubular forms are preserved in such a way because of quick diagenesis preventing significant compaction.

Nereites is a typical pascichnion produced by an unknown tracemaker (see discussion by Rindsberg 1994; Uchman 1995; Mángano et al. 2002) and is common in less energetic, fine-grained, full marine deposits.

Palaeophycus Hall, 1847

Palaeophycus cf. *tubularis* Hall, 1847

Fig. 8d

Description. Horizontal, slightly winding, thinly lined tubular burrow, about 1.5 mm in diameter. It occurs in Triassic laminated fine-grained sandstones.

Remarks. *Palaeophycus* is a mostly simple, open tubular burrow produced mainly by polychaetes and other deposit-feeding, carnivorous or omnivorous invertebrates (Pemberton & Frey 1982; Keighley & Pickerill 1995).

Phycosiphon Fischer-Ooster, 1858

Phycosiphon *incertum* Fischer-Ooster, 1858

Figs. 7b, d, 8a–c

Description: Horizontal, curved, small repeated lobes encircled by a thin marginal tunnel. The lobes are 2–4 mm wide and up to 17 mm long. The marginal tunnel is 0.6–2 mm wide. In cross-section, the trace fossils are seen as small spots, 1–1.5 mm across, with a dark core and a light mantle (*Anconichnus* preservation).

Remarks. Wetzel & Bromley (1994) discussed *Phycosiphon* and concluded that *Anconichnus horizontalis* Kern is the junior synonym of *Phycosiphon*. *Phycosiphon* is common in fine-grained, less energetic marine sediments.

Planolites Nicholson, 1873

Planolites isp. A and B

Figs. 8e, 10b

Description. Morphotype A (Fig. 8e). Horizontal to oblique simple, straight tubular structures, 5 mm in diameter, occurring in Permian sediments. Morphotype B (Fig. 10b). Horizontal to oblique simple, curved tubular structures, 2–3 mm in diameter occurring in Triassic laminated fine-grained sandstones.

Remarks. *Planolites* is interpreted as a pascichnial, actively filled burrow without any wall, produced by organisms belonging to different taxonomical groups; it displays a wide environmental range in marine and non-marine sediments (Pemberton & Frey 1982; Keighley & Pickerill 1995).

Teichichnus Seilacher, 1955

Teichichnus isp.

Fig. 8f

Description. Wall-like, sub-vertical spreite structure seen in cross-section as an 18–26 mm wide, at least 75 mm high zone, filled with meniscate-like, concave structures. Margins of the zone are uneven.

Remarks. *Teichichnus* is a dwelling/feeding structure, produced by a worm-like organism which migrated up, rarely down, keeping pace with sedimentation. It is common in shoreface and offshore sediments. Its mass occurrence is common in brackish water bays and lagoons (e.g., Pemberton et al. 2001).

Thalassinoides Ehrenberg, 1944

Thalassinoides suevicus (Rieth, 1932)

Fig. 9a

Description. Horizontal, straight to slightly winding, branched tubular burrows, 12–30 mm wide. The branches are Y-shaped, with swellings up 30 mm. Some specimens display 1–1.5 cm thick “teichichnoid” shifts in the vertical plane.

Remarks. This trace fossil was found in a loose block of a Triassic sandstone. *Thalassinoides* is a domichnial and fodinichnial burrow system produced mostly by decapod crustaceans (Frey et al. 1984). It is most typical for the shelf sediments as common representative of the *Cruziana* ichnofacies; however, it may occur in other full marine or brackish setting (see Fürsich 1973; Ekdale 1992; Schlirf 2000; and references therein).

Thalassinoides isp. A

Fig. 9b

Description. Mostly horizontal to subhorizontal, slightly undulating, straight to slightly curved, branched tubular trace fossil without walls, 6 mm in diameter. A swelling is seen in the branching points. It occurs in fine-grained laminated Triassic sandstones.

Remarks. The branches and swellings point to *Thalassinoides*, produced by small crustaceans.

?*Thalassinoides* isp. B

Fig. 9c, f

Description. Mostly horizontal to sub-horizontal, but also with vertical shafts, straight to slightly curved, rarely branched tubular trace fossil without walls, 10–22 mm in diameter, local swellings up to 35 mm can be present.

Remarks. Locally, ?*Thalassinoides* isp. B is cross-cut by *Chondrites* and *Zoophycos*.

Zoophycos Massalongo, 1855

Zoophycos isp.

Figs. 7c, 8c, 9d–g

Description. Endichnial, horizontal, sub-horizontal to inclined, or rarely steeply inclined planar spreite structure forming wide tongues of half-circles with lobed margins. The tongues

or lobe structures are 115–190 mm wide and 80–280 mm long. The half circles are about 150 mm in diameter. In most of them, fine, spreite laminae run more or less parallel to the tongue front and margins. Some fragments of the spreite display laminae-forming arcuate, fan-like or flabellate bundles. Some tongues became wider in the frontal part than at the base. Tongues of adjacent levels display different orientation: it is probable that they are helically arranged. In some specimens, the spreite are filled with darker and finer material than the surrounding rock. The planar spreite structures are seen in cross-section as 3–6 mm wide bands filled with menisci-like structures. This trace fossil occurs in sandstones and fine-grained sediments. Vertically, *Zoophycos* extends at least 220 mm.

Remarks. The planar spreite structure and menisci-like structure seen in cross-section resulted from lateral migration of the causative burrower.

The producer of *Zoophycos* s.l., possibly a sipunculid (Wetzel & Werner 1981), polychaete arthropod (Ekdale & Lewis 1991) or an echiuran worm (Kotake 1992), remains unknown. Details of its feeding strategy are a matter of controversy (e.g., Bromley 1991; Locklair & Savrda 1998; MacEachern & Burton 2000; Kotake 2015; Löwemark 2015). The upper helical part of *Zoophycos* (Pliocene, Rhodes, Greece and Miocene of Austria) is interpreted as a deposit-feeding structure, and steeply inclined lateral lobes coming out from its basal part are considered as sulphide wells for chemosymbiotic bacteria (Bromley & Hanken 2003; Pervesler & Uchman 2004). The *Zoophycos* producer probably had different modes of feeding depending on the situation.

Creeping traces A and B

Fig. 10a–c

Description. Type A (Fig. 10a, b) is represented by horizontal, slightly winding very shallow grooves or threads, up to 1 mm wide. Type B (Fig. 10c) occurs as horizontal, slightly winding very shallow grooves, 4 mm wide, with slightly elevated, uneven margins, and a thin lining on the bottom. It is locally filled with sandstone from overlying lamina. Cylindrical structures marked as grooves on the surface of lamina are probably of the same origin.

Remarks. These structures are seen on parting and bedding surfaces of fine-grained, laminated Triassic sandstones. They could be produced by small, crawling invertebrates, probably molluscs or crustaceans.

Small vertical structures

Fig. 10d

Description. Small knobs, 2–3 mm in diameter, seen on parting and bedding surfaces of fine-grained Triassic sandstones. Some of them are surrounded by a concentric ring or collar, which is 5–8 mm in diameter.

Remarks. The knobs are cross-sections or terminations of vertical burrows, the geometry of which remains unknown. It is possible that they could belong to the ichnogenus *Skolithos* Haldeman. Alternatively, they might also be gas-escape structures. They co-occur with sub-circular rings (13–20 mm in diameter) or elliptical tongues (13–37 mm wide) with concentric structure (Fig. 10d), which may also be surface or shallow-subsurface gas-expulsion structures in more fluid sediment.

Systematic description of borings

Conchotrema Teichert, 1945

cf. *Conchotrema* isp. A

Figs. 12a, 13e

Description. Tubular, straight or curved, or contorted, densely branched fillings of tubes inside brachiopod shells, which form galleries of horizontal tubes and variable, irregularly distributed branches, some of which run obliquely or vertically with respect to the shell surface. The tubes are 0.25–0.3 mm in diameter. They show frequent, variable branches at acute or right angles. Some of the branches show Y-shaped dichotomy, while others can interpenetrate. Some tubes were preferentially silicified and remain loose after dissolution of shells (Fig. 12a).

Remarks. Some authors (Voigt 1972; Bromley 2004) consider *Conchotrema* to be a junior synonym of *Talpina*, but it is still in use. Common branches and irregular geometry suggest *Conchotrema*, but the diameter of this boring is usually smaller than 0.2 mm (Rodriguez & Gutschick 1970). *Conchotrema* is produced by phoronids (Voigt 1975).

cf. *Conchotrema* isp. B

Fig. 12c, e, g, h

Description. Tubular, straight, gently curved, slightly winding or locally contorted, branched borings inside brachiopod shells, which show gentle swellings and constrictions. The swellings expand symmetrically or on one side of the cylinder. The diameter ranges from 0.025 to 0.065 mm. It shows branches at acute or right angles. It is not clear if some of the tubes interpenetrate or just miss each other.

Remarks. The diameter of this trace fossil is a magnitude smaller than other borings referred to *Conchotrema*. *Chaetophorites* Pratje, 1922 is similar, but its diameter is smaller than 0.02 mm. The swellings suggest bryozoans as the tracemakers.

Oichnus Bromley, 1981

cf. *Oichnus* isp.

Fig. 13c

Description. A simple, almost rounded hole, perpendicular to the shell surface, 0.7–0.9 mm in diameter. The holes are irregularly distributed.

Remarks. The hole resembles *Oichnus* Bromley, 1981, a predatory boring of gastropods; however, their outline is not perfectly rounded as it is in *Oichnus*. It is unclear if this is a primary feature or an effect of etching of the silicified shells. For taxonomic problems of *Oichnus* see Wisshak et al. (2015).

Palaeosabella Clarke, 1921

Palaeosabella prisca (McCoy, 1855)

Fig. 12f

Description. Club-like simple boring, narrower in the proximal part and wider in the distal part with hemispherical termination, 5–6 mm long and 0.7–1.2 mm wide.

Remarks. These borings have been observed in longitudinal section. Their observed outline shape probably depends on the inclination of the sectioning plane to the axis of the boring. *Palaeosabella prisca* is produced probably by polychaetes (Bromley 2005).

Palaeosabella isp.

Description. Torpedo-shaped clubs, which are 5 mm long and 0.8 mm wide in the perimeter.

Remarks. Such small torpedo-like borings are produced by recent polychaete *Stylarioides* and sipunculoid *Dendrostomum* (Bromley 1970).

Pinaceocladichnus Mayoral, 1988

Pinaceocladichnus isp.

Fig. 12b

Description. Tubular, straight or gently curved, branched borings inside brachiopod shells, which show gentle swellings and constrictions. The branches can be thinner than the main cylinder. The external diameter ranges from 0.07 to 0.13 mm. It shows frequent, variable branches at acute or right angles. Some of the branches show Y-shaped dichotomy. Some of the tubes interpenetrate.

Remarks. The swellings and constrictions, and the rectangular style of branching point to *Pinaceocladichnus*, which is a ctenostomate bryozoan boring known to have occurred since the Ordovician (Mayoral 1988; Botquelen & Mayoral 2005).

Rogerella Saint-Seine, 1951

Rogerella isp.

Fig. 13a, b

Description. Pouch-like depressions on the external surface of productid and spiriferid brachiopod shells, more commonly on the pedicle valve. They are oriented more or less perpendicular to the shell surface and display a slit-like cross-section, which is 0.9–3 mm long and maximally 0.3–1 mm wide. The boring is wider from one flank and narrower from the

other. It is scattered irregularly on the surface or rarely along placcation on both sides of the sulcum.

Remarks. This is an acrothoracican barnacle boring, known since the Devonian (Codez & Saint-Seine 1957; Rodriguez & Gutschick 1977), commonly in various skeletal elements. Seilacher (1969) suggested that the acrothoracican barnacle bored preferentially living hosts, but this was questioned (Rodriguez & Gutschick 1977). Some shells of Permian brachiopods display evidence of organism reaction to the borings (Schlaud & Young 1960; Cooper & Grant 1972, 1974). Seilacher (1969) noted that they prefer umbos, ribs and edges of productid brachiopods from the Namurian of Libya.

Talpina von Hagenow, 1840

?*Talpina* isp. A

Fig. 13d, f

Description. Tubular, straight or slightly curved, borings inside brachiopod shells, which are 0.3–1 mm in diameter. They run more or less parallel to the shell surface. They show rare branches at acute angles; some of them run vertically at a right angle to the shell surface. The surface is uneven (Fig. 13d), probably because of overgrowth by silica, or rarely smooth (Fig. 13f). Some tubes are hollow.

Remarks. Limited insight into the geometry of this boring prevents any stricter determination. The characteristic features of this ichnogenus, i.e., the radial arrangement, lateral branches only on one side, apertures regularly distributed above branching points, lack of anastomosing (Bromley & D'Alessandro 1987), cannot be fully confirmed. *Talpina* has been considered previously as a bryozoan boring (e.g., Bromley 1970; Kennedy 1970), and is referred later to phoronids (Voigt 1972, 1975; Bromley 2004).

?*Talpina* isp. B

Fig. 12d

Description. Tubular, straight, curved, rarely branched fillings of tubes inside brachiopod shells. The branches run commonly at an acute angle in respect to segments in proximity of

the horizontal gallery and curve gently backward distally. The tubes are 0.17–0.25 mm in diameter.

Remarks. Branches are noted only on one side, as in *Talpina* (see Bromley & D'Alessandro 1987).

Contorted tubes

Fig. 12(h)

Description. A simple tube, 0.12–0.16 mm in diameter, observed at the distance of about 1.5 mm, showing gentle to sharp turns in variable planes. The tube shows gentle constrictions. Terminations of the tube are not preserved.

Remarks. It is not obvious if this is a trace fossil (boring) or body fossil (the tube of a worm).

Small galleries

Fig. 13b, c

Description. Numerous, straight, slightly winding or curved, branched hollow tubes which form galleries composed of horizontal and oblique segments and numerous branches running to the shell surface, where they are visible as holes. The holes are irregularly distributed or arranged in short, curved rows. The tubes are 0.16–0.22 mm in diameter.

Remarks. It is not excluded that this boring is a preservational variant of *Talpina* von Hagenow, 1840, or *Conchotrema* Teichert, 1945, but its poorly recognized geometry prevents closer determination. Borings of this type can be produced by bryozoans or phoronids (Bromley 1970).

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