

Scratch circles from the Ediacaran and Cambrian of Arctic Norway and southern Africa, with a review of scratch circle occurrences

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Scratch circles—bedding plane parallel sedimentary structures formed by the passive rotation of a tethered organism into the surrounding sediment—are relatively rare in the geological record. Here new occurrences of scratch circles are described from the Ediacaran–Cambrian Stáhpogieddi Formation, Digermulen Peninsula, Arctic Norway, and from the Ediacaran Nudaus and Urusis formations, Nama Group, of southern Africa. A literature survey confirms a previously noted concentration of scratch circles reported from shallow marine upper Ediacaran–lower Cambrian and paralic Carboniferous rocks. Scratch circle identification and nomenclature are discussed. The stratigraphical range of the trace fossils *Treptichnus pedum* and *Gyrolithes* isp. in the Stáhpogieddi Formation are extended downward. Combined with earlier reports of *Harlaniella podolica* this adds new precision to the placement of the Ediacaran–Cambrian boundary on the Digermulen Peninsula.

Key words. scratch circles, Ediacaran, Cambrian, Norway, Republic of South Africa, Namibia, trace fossils

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Scratch circles are bedding-plane parallel sedimentary structures formed by the current-induced rotation of an organism attached to or partially inserted in the sediment, generating complete or partial circular impressions into the surrounding sediment (*e.g.* Allen 1982). Today they are most commonly observed in a sub-aerial setting due to wind-induced rotation of grass, or other plants (Fig. 1A, B). They also form sub-aqueously (*e.g.* Langerfeldt 1935, Ewing & Davis 1967) and this is the environment in which most fossil scratch circles formed. They are typically preserved as casts on bed soles (Fig. 1C) but are also found occasionally on bed tops (Fig. 1D). In a comprehensive text on sedimentary structures Allen (1982, p. 521–522) outlined the general characteristics and formation of scratch circles, including a single record of a scratch circle in the geological record, documented by Prentice (1962) from Cretaceous rocks of England. Although many additional occurrences are known, several of which were initially interpreted as body fossils or trace fossils (review in Jensen *et al.* 2002), they remain a relatively rare—or rarely reported—sedimentary structure. Possibly the earliest

[FIGURE 1 NEAR HERE]

identification of a fossil scratch circle was made by Nathorst (1886) who compared a structure from the lower Cambrian *Mickwitzia* sandstone of south-central Sweden with circles formed by the wind-induced rotation of a plant (Fig. 2). Recognition of scratch circles is relatively straightforward in forms developed as arcs covering a sector of a circle emanating from a knob at the centre of curvature (Fig. 1C). Scratch circles developed as full circles with concentric ridges covering most of the disc (Fig. 1E), on the other hand, have morphologies similar to those of simple discoidal Ediacara-type fossils, as well as to casts of

the impressions of hydrozoan and scyphozoan medusae; Richter (1926) tellingly referred to scratch circles as “Scheinquallen” (illusory jellyfish). Awareness of the potential confusion of scratch circles with medusoid body fossils has a long history, in fact. In an early (1860's) discussion on the interpretation of Ediacara-type fossils from England, A.C. Ramsay suggested a scratch circle origin for *Charniodiscus* holdfasts from Charnwood Forest (see Howe *et al.* 2012). Although clearly a body fossil in this example, there will undoubtedly be cases where a confident distinction between a scratch circle and a body fossil or trace fossil will not be possible.

[FIGURE 2 NEAR HERE]

The purpose of this paper is to (1) discuss scratch circle terminology and identification; (2) report new occurrences of Ediacaran and Cambrian scratch circles; and (3) provide an updated list of fossil scratch circles reported in the literature.

Scratch circle terminology

The term scratch circle has been used collectively for full-circle specimens but also for specimens developed over only a sector of a circle. In some papers the latter have been referred to as scratch semi-circles (Kukal & Al-Naqash 1970, Rygel *et al.* 2006), but in a strict sense this nomenclature does not describe the full range of incomplete scratch circles. Another term for incomplete forms, flag scratch circle (Uchman & Rattazzi 2013), alludes to the fact that, like a flag, incomplete scratch circles may indicate direction of flow (although according to Allen 1982 scratch circle orientation is only weakly related to current). Other

terms for scratch circles include “Scharkreis”, a German term introduced by Richter (1926) that is also used in English, and sweep mark or swing mark (*e.g.* Osgood 1970; Gary *et al.* 1972). Somewhat related types of structures are “Schwoimarken” (a German term translating as swing marks, see Vallon *et al.* 2015). These have been interpreted as made by dead organisms moved by currents and are mainly reported from the Jurassic Solnhofen lithographic limestone, Germany. Although the causative organisms may have become anchored, the resulting imprints are more irregular than those of scratch circles. Furthermore, Vallon *et al.* (2015) suggested that most of these Schwoimarken are better interpreted as structures related to arthropod ecdysis. Radial elements are rarely observed in scratch circles, but are important as they may provide imprints of the spun-around organism (*e.g.* Fig. 1F; Osgood 1970, pl. 71:3; Jensen *et al.* 2002, figs 1, 2). Uchman & Rattazzi (2013) proposed to name radial elements as gnomon from their resemblance to the pin in a sundial. Even more rarely remnants of the organism may be preserved in the central part of the scratch circles; parts of crinoid stems (Osgood 1970) and the foraminifer *Bathysiphon* (Uchman & Rattazzi 2013) constitute the clearest examples.

Figure 3 presents a summary of scratch circle terminology. As with other terms for sedimentary structures first introduced for supposed organisms, such as *Kinneyia* (*e.g.* Bouougri & Porada 2007), the term *Kullingia* (without italics) scratch circle can be usefully retained to denote complete scratch circles.

Taxa erected on scratch circles

Although an organism was involved in their formation, scratch circles are neither body fossils nor are they trace fossils as they do not represent a biological activity. Formal taxa erected on

the basis of scratch circles are therefore invalid. Scratch circles from the lower Cambrian Torneträsk Formation, northern Sweden (Figs 1E, F) (Stodt 1987, Jensen *et al.* 2002) were first reported as the Ediacara-type fossil *Madigania annulata* Sprigg (*e.g.* Kulling 1964), and later formed the basis for the new taxon *Kullingia concentrica* (Glaessner in Føyn & Glaessner 1979). Combinations involving *Kullingia* should be avoided and species assigned to *Kullingia* relocated. The combination *Kullingia delicata*, based on *Cyclomedusa delicata* Fedonkin, was used for scratch circles from the basal Cambrian Chapel Island Formation of Newfoundland (Narbonne *et al.* 1991). The type material of *Cyclomedusa delicata* from the White Sea area of northern Russia (Fedonkin 1981) is probably a body fossil. *Kullingia jixianensis* described by Niu (1987) from the Mesoproterozoic Yangzhuang Formation, Jixian County, northern China is similar to a range of problematic Proterozoic discoidal structures (body fossils?) described from northern China (*e.g.* Luo *et al.* 2016). Finally, Tang *et al.* (2016) erected *Kullingia rotadiscopsis* for concentric carbonaceous rings from the late Ediacaran Doushantou Formation, South China. This is a body fossil and the species needs to be re-assigned. *Suzmites* Fedonkin from the late Ediacaran of Russia (*e.g.* Fedonkin 1981) probably is a scratch circle but in the absence of evidence for an anchor point it could also be comparable to Schwoimarken (see above). It has been suggested (*e.g.* Fedonkin 1976) that *Suzmites* was formed by *Pteridinium*. *Droserinus arcuatus* McMenamin from the lower Cambrian Puerto Blanco Formation of Mexico consists of concentric structures covering 60 to 70 degrees of an arc (McMenamin 2001). It may be a scratch circle although McMenamin's (2001) alternative interpretations as arthropod-type trace fossils or de-mineralized brachiopod shells are reminders of the uncertainties in the interpretation of such morphologically simple structures. Osgood (1970) demonstrated that *Dystacophycus* Miller and Dyer, from the Ordovician of Ohio, is a scratch circle. Osgood's (1970) scratch circle

interpretation of the purported porpitiid *Palaeoscia floweri* Caster from the Ordovician of Ohio seems plausible, but the type material possesses fine radial elements in the central part of the disc that are unusual for scratch circles. While some of the specimens that Osgood (1970, pl. 71:3, pl. 82:4) included in *Palaeoscia floweri* clearly are scratch circles, it is less clear if this applies also to the type material (see also Collette *et al.* 2011 for discussion of *Palaeoscia floweri*). *Aysenspriggia* Bell *et al.* from the Cretaceous of Chile (Bell *et al.* 2001) is also likely to be a scratch circle.

[FIGURE 3 NEAR HERE]

Scratch circle identification

Identification of a scratch circle is generally straightforward in forms developed as arcs covering a sector of a circle, typically with greatest depth distally and with a central attachment point represented by a knob or pimple in hyporelief preservation (Fig. 1C). In specimens where there is no evidence for an attachment point identification can be more problematic, for instance, as is the case with probable Ediacaran scratch circle *Suzmites* (discussed above). In younger occurrences the alternative possibility of an arthropod type scratch mark must be considered. For example, this was correctly done by Hughes *et al.* (2013) for *Suzmites*-like probable scratch circles from the Cambrian Parahio Formation, Spiti, India (see also discussion on *Droserinus* above).

Scratch circles developed as discs range in vertical profile from flat to conical and with concentric ridges developed over the full disc or only distal parts. The distinction between scratch circles and certain body fossils and trace fossils can be complicated. Some

specimens first described as imprints of porpitiid hydrozoans (“chondrophorine floats”) or Ediacara-type fossils are indeed better interpreted as scratch circles (*e.g.* Jensen *et al.* 2002, Kolesnikov *et al.* 2015). Most discoidal Ediacara-type fossils were probably holdfasts of more extensive, frondoid organisms (*e.g.* Gehling *et al.* 2000, Serezhnikova 2014, Tarhan *et al.* 2015), while others may have been microbial colonies (Grazhdankin & Gerdes 2007). Distinction from scratch circles is obvious in forms with extensive radial elements but there are Ediacara-type body fossils with only concentric ornamentation and these may have a central boss. The concentric ornamentation may have originated as a taphonomic feature during compaction and collapse of the holdfast (*e.g.* Gehling *et al.* 2000), in which case the concentric features are likely to be blunt. Other discs show possible evidence for rigid internal structures (*e.g.* Hofmann *et al.* 2008) and in this case imprints could be similar to that of a scratch circle. Sharp, relatively deeply-impressed ridges and a central boss favour the interpretation as a scratch circle as does a preserved impression of the organism tool (Fig. 1F). Other features consonant with a scratch circle interpretation include an even spacing and thickness of the concentric grooves/ ridges round the whole circle/sector as well as the development of grooves/ridges within several successive sedimentary laminae. Overlapping specimens also suggest a scratch circle origin as does the presence of otherwise similar ridges but with a divergent orientation attributed to an uprooted tube (Jensen *et al.* 2002, fig. 1H). A scratch circle may be repeated vertically through successive laminae but unlike Ediacara-type body fossils will not be a three-dimensional structure with volume. Where possible, the examination of large numbers of specimens may reveal unambiguous features indicative of a scratch circle or body fossil interpretation. For example, flag scratch circles associated with complete discs of potentially problematic interpretation favour a scratch circle origin for the whole assemblage (such as material figured by Lucas 2011 and Lerner & Lucas 2015).

Scenella-type skeletal fossils may be superficially similar to scratch circles, for example material described by Yang *et al.* (2014) from the lower Cambrian of China, but differ fundamentally in being preserved in positive epirelief.

Scratch circles consisting of a few or single concentric ridges can also be confused with the trace fossils *Laevicyclus* (see Knaust 2015 for a review of this ichnotaxon and potential examples). Material with numerous fine ridges and overlapping specimens from the Carboniferous of Menorca, identified as *Laevicyclus* by Llompart & Wieczorek (1997, pl. 2:3), are clearly scratch circles. The interpretation of specimens in the same study that consist of simple rings surrounding a central boss (Llompart & Wieczorek 1997, pl. 2:1) is more uncertain, and these could be trace fossils resulting from feeding activity around a vertical burrow (D' Alessandro 1980, being a further example).

[FIGURE 4 NEAR HERE]

New occurrences of Ediacaran and Cambrian scratch circles

New Ediacaran and Cambrian scratch circle localities and specimens from Arctic Norway and southern Africa are described in the following sections. Additionally, scratch circles from the Triassic of Germany previously reported in an unpublished thesis (Kellner 1995) or internet web page (www.steinkern.de) are figured (Fig. 1C, D).

Scratch circles from the Stáhpgieddi Formation (Ediacaran–Cambrian) of Finnmark, Arctic Norway

The Digermulen Peninsula, Arctic Norway, yields a predominantly siliciclastic succession that is several kilometres thick and extends from Cryogenian diamictites of the Smalfjorden Formation at the base to Lower Ordovician rocks at the top (*e.g.* Banks *et al.* 1971) (Fig. 4). During fieldwork in 2016 by members of the Digermulen Early Life Research Group, scratch circles were recovered from three localities within the Ediacaran–Cambrian Manndrapselva Member of the Stáhpogieddi Formation (Fig. 4A). The Manndrapselva Member consists of three cycles (parasequences – McIlroy & Brasier 2017), commencing with a basal sandstone abruptly but conformably overlying fine-grained sediment of the Indreelva Member (Fig. 4C). There follows two upwards coarsening sequences with siltstone and sandstone event beds in their lower parts and sandstone-dominated upper parts that are interpreted as turbidite to shallow marine regressive cycles (Banks 1970, 1971). The overlying Lower Member of the Breidvika Formation consists of a several upwards-coarsening cycles that are thinner compared to those of the Manndrapselva Member.

Two scratch circles were found low down in the third cycle of the Manndrapselva Member. A specimen with a radius of some 15 mm from a section along the Manndrapselva river (Fig. 4B) (70°34′34.3″N, 28°06′50.9″E) consists of around 18 delicate sharp ridges preserved on the base of a thin siltstone laminae (Fig. 5A). Ridges are preserved over a sector of about 150 degrees with a relatively regular spacing between ridges from 0.4 mm to 0.6 mm. There is no evidence for a central attachment point but a scratch circle origin is obvious from the nature of the sharp delicate ridges, comparing closely to scratch circles from the lower Cambrian of northern Sweden (*cf.* Jensen *et al.* 2002, fig. 1). A second specimen (Fig. 5B), from coastal outcrops along a narrow unnamed gorge (Fig. 4B) (70°35′47.9″N, 28°12′17.3″E), is preserved in negative epirelief in sandstone. The counterpart was not encountered but a rubber cast (Fig. 5B) shows nine relatively blunt ridges over a sector of

about 135 degrees; these appear not to have natural terminations. The radius is approximately 12 mm.

[FIGURE 5 NEAR HERE]

Poor preservation impedes precise measuring of ridge spacing but this is approximately 1 mm. It is not clear if these specimens are flag scratch circles or incompletely preserved *Kullingia* scratch circles.

Flag scratch circles consisting of a central plug and blunt, single, double or triple ridges (Fig. 5C) were collected from the basal part of the Manndrapselva Member along the Manndrapselva river (Fig. 4B) (70°34'35.6''N, 28°07'48.4''E). They are preserved in thin sandstone beds from an interval dominated by thin-bedded sandstone and red-coloured shale. There are at least five readily identifiable specimens with a radius of 3 mm to 13 mm. This material is comparable to better preserved specimens from the late Ediacaran of the White Sea area figured by Jensen *et al.* (2002, fig. 3A).

Discoidal Ediacara-type fossils occur in the underlying siltstone and fine sandstone-dominated Indreelva Member (Farmer *et al.* 1992, Högström *et al.* 2013). None of the published specimens are likely to be a scratch circle. A possible scratch circle was collected from the lower part of the Indreelva Member by the Digermulen Early Life Research Group in 2015, along a coastal section to the south of the Manndrapselva river. This is a large (radius > 150 mm) discoidal form with relatively blunt ridges and no evidence for a central boss. Portions of the concentric banding show a diverging orientation (Fig. 5D). The same interval yields discoidal Ediacara-type fossils (Högström *et al.* 2014), some of which are of

comparable dimensions to the here figured specimen, and it remains uncertain if this is a scratch circle or, perhaps more likely, a deformed body fossil.

Finally, it may be noted that discoidal structures have been described from the lower Cambrian Breidvika Formation on the Digermulen Peninsula, identified as *Cyclomedusa*, *Nimbia* and *Tirasiana* (Crimes & McIlroy 1999). Although it may be doubtful if these are body fossils, a scratch circle origin does not seem likely.

[FIGURE 6 NEAR HERE]

Stratigraphical context of Manndrapselva Member scratch circles

The Manndrapselva Member contains the local Ediacaran–Cambrian boundary, biostratigraphically constrained by trace fossils, acritarchs, sabelliditids and the late Ediacaran problematica *Palaeopascichnus* and *Harlaniella* (Högström *et al.* 2013, McIlroy & Brasier 2017). The basal part of the Manndrapselva Member yields rare *Palaeopascichnus* (Banks 1970, McIlroy & Brasier 2017) with *Harlaniella* occurring in the second cycle (McIlroy & Brasier 2017, and pers. obs. 2016) approximately 40 m above its base. Högström *et al.* (2013) reported Cambrian-type trace fossils approximately 12 metres below the top of the member in coastal outcrops some 300 m northeast of the coastal scratch circle-locality reported here. A specimen of *Treptichnus pedum* (Fig. 6C) reported here from the scratch circle-bearing coastal section some two meters above the scratch circle level (Fig. 6A), is about 10 m down-section of the *Treptichnus pedum* reported in Högström *et al.* (2013) and within 10 m of the base of the third cycle. In addition, the vertical spiral trace fossil *Gyrolithes* isp. (Fig. 6B) was observed some two metres below the scratch circle level. At this

level also occur dark filamentous fossils—probably sabellidites—that are currently under study. Both *Treptichnus pedum* and *Gyrolithes polonicus* are generally considered indicative of a Cambrian age although both extend a few metres below the level of the basal Cambrian GSSP in Newfoundland (Gehling *et al.* 2001). These new trace fossil data, combined with earlier reports of *Harlaniella* biostratigraphically constrain the Ediacaran–Cambrian boundary on the Digermulen Peninsula to an interval spanning the basal part of the third cycle of the Manndrapselva Member down to the sandstone-dominated, and to date unfossiliferous, upper part of the second cycle (Fig. 4C).

The Torneträsk Formation, from which *Kullingia* scratch circles were first described from sections north and south of Lake Torneträsk, northern Sweden (Fig. 4A), has generally been considered a thinner correlative of parts of the succession on the Digermulen Peninsula (*e.g.* Føyn & Glaessner 1979). The vast majority of scratch circles in the Torneträsk Formation originate from the upper part of the Lower Siltstone Member of Thelander (1982), or Middle Sandstone of earlier authors (*e.g.* Kulling 1964). They overlie Cambrian-type trace fossils and occur with *Sabellidites*. *Platysolenites* is found in overlying units; a basal Cambrian (Fortunian) age is indicated for these scratch circles (*cf.* Jensen & Grant 1998). Here it should be noted that Nielsen & Schovsbo's (2011) placement of the Middle Sandstone in the Torneträsk area in Cambrian Stage 3 on the basis of sedimentary sequence identification is implausible. Lithostratigraphical correlation has been traditionally made between the Manndrapselva Member on the Digermulen Peninsula and the Middle Sandstone in the Torneträsk area (*e.g.* Stodt *et al.* 2011, fig. 58.3). The biostratigraphical context suggests that scratch circles in the Manndrapselva Member are older than those of the Middle Sandstone of the Torneträsk Formation. The scarce Digermulen Peninsula material limits the scope for comparison, but it may be noted that the Torneträsk material consists of *Kullingia*

scratch circles and includes specimens of larger dimensions than those of the Manndrapselva Member.

Scratch circles from the Nama Group (late Ediacaran) of southern Africa

Scratch circles are reported for the first time from the Nama Group on the basis of material from the Witputs sub-basin of the Nama foreland basin from southern Namibia and northern South Africa (Fig. 7). Discoidal Ediacara-type fossils are rare in the Nama Group, which instead is characterized by transported petalonamids such as *Ernietta*, *Pteridinium* and *Swartpuntia*. *Paramedusium africanum*, known from a single incomplete specimen in the Witputs sub-basin in Namibia and questionably attributed to the Nasep Member, differs from scratch circles in its possession of fine radial ribs. Darroch *et al.* (2016) reported *Aspidella* from an unspecified part (probably the Vingerbreek Member) of the Schwarzrand Subgroup in the northern Zaris sub-basin in Namibia. Unlike the scratch circles reported here, these discs lack any concentric ornamentation.

[FIGURE 7 NEAR HERE]

Scratch circles from the Nudaus Formation (late Ediacaran), northern South Africa

The Nama Group in the Vioolsdrif area, Northern Cape, Republic of South Africa (RSA) commences with shallow marine and fluvial siliciclastics and platform carbonates of the Dabis and Zaris formations (Kuibus Subgroup) (Germs & Gresse 1991, Gresse *et al.* 2006, Germs & Gaucher 2012). Carbonates of the Zaris Formation yield the late Ediacaran skeletal

fossil *Cloudina* and *Namacalathus* (Gresse *et al.* 2006, Almond 2009). The Nudaus Formation (Schwarzrand Subgroup) begins with sandstone of the Niederhagen Member, followed by the shale-dominated Vingerbreek Member (Fig. 8). The Vingerbreek Member in southern Namibia has been interpreted as a muddy tidal deposit (Germs & Gresse 1991) in places with strong microbial mat signature (*e.g.* Bouougri & Porada 2007) whereas the upper part of the member in the Springbok and Vioolsdrif areas has been interpreted as storm-influenced shallow marine deposits. The correlation of the Niederhagen Member in the RSA with the type area in Namibia is somewhat equivocal (Germs & Gaucher 2012). Near Vioolsdrif the Niederhagen Member quartzites are associated with pre-Vingerbreek channel incision (sequence boundary) and feature microbially induced sedimentary structures (MISS) as well as small-scale lenticular channel bodies and an intertidal to shallow subtidal interpretation is possible. The overlying finely-laminated mudrocks and subordinate quartzites of the Vingerbreek Member build a succession of upward-shoaling parasequences that are thick and of extensive outcrop area. An offshore to nearshore shelf depositional setting, below fairweather wave base but with some tempestite influence, seems likely (see also Pflüger & Gresse 1996). Palaeochannels in the Vingerbreek Member at Vioolsdrif were interpreted by Germs & Gaucher (2012) as formed in response to a distant glacial event. Trace fossils (mainly bedding parallel) and tubular/filamentous fossils have been described from the Vingerbreek Member in Namibia (*e.g.* Crimes & Germs 1982, Bouougri & Porada 2007, Cohen *et al.* 2009), and South Africa (Gresse *et al.* 2006, Almond 2009 and pers. obs.). The Vingerbreek Member at Vioolsdrif measures c. 182 m (Almond 2009), and is constrained by radiometric ages in over- and underlying rocks elsewhere in the Nama Basin to between 547 and 543 Ma (see Bowring *et al.* 2007, Grotzinger & Miller 2008, Schmitz 2012). Overlying the Vingerbreek Member near Vioolsdrif, the Schwarzrand Subgroup continues

with quartzarenites of the Nasep Member followed by a great thickness

[FIGURE 8 NEAR HERE]

of black carbonates and minor siliciclastics (Huns, Feldschuhhorn and Spitskop Members), terminating with basal breccias of the early Cambrian Nomtsas Formation (Almond 2009).

A scratch circle (Fig. 9A, B) was collected by John Almond in 2008 (Almond 2009) on a platy float block of grey-green siltstone from the lower part of the Vingerbreek Member (Nudaus Formation, Schwarzrand Subgroup, Nama Group) on the eastern face of the Neint Nababeep Plateau (28°51'41.7''S, 17°36'27.2''E), *c.* 10.26 km south of Vioolsdrif. The scratch circle slab was collected from just above a small, prominent-weathering ledge of laminated to thin-bedded siltstone and fine-grained sandstone approximately 80 m from the base of the Vingerbreek Member (Fig. 8) *i.e.* towards the bottom of the second thick, upward-shoaling parasequence within the Vingerbreek Formation. This scratch circle is preserved as a positive disc (inferred hyporelief) and is elliptical—probably due to tectonic distortion—in plan view measuring 60 mm by 48 mm in diameter. It features prominent concentric ridges, a distinct outer margin and a small central pimple. This is a Kullinga scratch circle with considerable similarity to a discoidal Ediacara-type fossil. A scratch circle interpretation is indicated by the sharply defined concentric ridges, a sharp outer margin, and the presence of a central pimple (Fig. 9A, B). The concentric lines are also inscribed on several successive thin laminae, favouring a scratch circle interpretation. There is a possible radial imprint of the rotated organism (Fig. 9A), although this appears not to terminate at the distal end of the disc and a chance association cannot therefore be excluded. A second slab with scratch circles from the same area was collected by Wendy Taylor and John Almond in 2016 from a slightly

lower stratigraphical level (Fig. 8). This second slab is an isolated float block of thin-bedded

[FIGURE 9 NEAR HERE]

fine-grained quartzite bearing two positive hypichnial scratch circles. It was collected on the banks of a deeply-incised stream gully at 28°51'39''S, 17°36'26''E, some 80 m SSE of the previous scratch circle locality. The slab is angular and has clearly not been transported far. It probably comes from a thin, prominent-weathering package of impure, greenish-grey quartzites showing an irregular bedding-parallel breakage and MISS textures that crops out at this locality. The horizon lies within the heterolithic uppermost third of the first thick, upward-shoaling parasequence within the Vingerbreek Formation and lies stratigraphically some 20 m below the previous scratch circle horizon. This consists of two overlapping partly preserved scratch circles each with a radius of about 70 mm (Fig. 9C). Within the discs are seen both somewhat coarser and finer ridges, with no obvious similarity in the arrangement of ridges between the two specimens. In the overlap zone, the concentric ridges on the right-hand side specimen largely efface those of the left-hand side specimen (Fig. 9C), further evidence for a scratch circle rather than body fossil origin. Both discs overprint faintly developed radial, apparently somewhat fan-shaped, ridges. Their relationship to the scratch circles is unclear.

Scratch circle from the Urusis Formation (late Ediacaran), southern Namibia

A scratch circle was recorded in the field by John Almond and Luis A. Buatois in April 2009 (not collected) on the NW slopes of Swartpunt Mountain, Farm Swartpunt, southern

Namibia. Approximate location 27°28'29''S, 16°41'37''E. The stratigraphic horizon is within the

[FIGURE 10 NEAR HERE]

lower part of Medium-scale Sequence 18 of Saylor (2003) in the Spitskop Member, Urusis Formation, Schwarzrand Subgroup. This is a siliciclastic interval between major limestone packages, below level of major slumps and *Pteridinium* and *Swartpuntia*. This occurrence is some 60-70m above an ash bed that has been dated as c. 541 Ma (see fig. 3 of Narbonne *et al.* 1997) and therefore very latest Ediacaran in age.

The single incomplete scratch circle (radius *c.* 4 cm) has numerous, fairly evenly-spaced, sharp concentric ridges and possible vague impression of tube-like, centrally attached structure (Fig. 10B). It is preserved as positive hyporelief on sole of tabular-bedded quartzite that also features numerous current-orientated, comb-like scratch sets (Fig. 10A).

Swartpuntia occurs in same zone as the scratch circle and might be the tool responsible for some of the scratch combs.

Discussion

There undoubtedly exist additional occurrences (reported or not) of scratch circles to those listed here (Table 1), but it is reasonable to infer that they really are a relatively rare sedimentary structure. Although scratch circles are distributed through geological time (Table 1), a previously noted concentration of occurrences (or reports) from Ediacaran–Cambrian shallow-marine and Carboniferous paralic and fluvial rocks (Jensen *et al.* 2002) is

maintained. Their formation and preservation require a combination of suitable organism tools, currents and preservational conditions. As with trace fossils, preservation is less likely to occur if such delicate, essentially two-dimensional sedimentary structures are exposed on

[TABLE 1 NEAR HERE]

the seafloor, where they may be readily effaced by wave or current action, bioturbation or collapse of surface sediment. The sharpness of the scratches implies incision into coherent sediment, such as consolidated mud. A situation of near-instantaneous scratch formation and sediment infilling of the impression favours preservation, although specimens showing vertical repetition through several sedimentary laminae suggest a more complex history of formation. In locations where they are found in great numbers, such as the Torneträsk Formation of northern Sweden, they are restricted to narrow stratigraphic intervals. With respect to both the Ediacaran–Cambrian transition and Carboniferous marginal marine strata, the limited intensity and depth of bioturbation would have favoured conditions both for scratch circle formation and the possibility of a scratch circle entering the rock record once formed (*cf.* Droser *et al.* 2002, Buatois & Mángano 2011). *Kullingia* scratch circles in both the Torneträsk and Chapel Island formations have yielded imprints of the likely tubular organism that generated the scratch circle (Jensen *et al.* 2002), but in both cases there is not enough information to confidently identify a producer. Jensen *et al.* (2002) suggested a sabellid, similar in morphology to the late Ediacaran *Saarina juliae*, as a producer of scratch circles from the Torneträsk Formation and noted that *Ladatheca cylindrica* is found in the same general interval of the Chapel Island Formation scratch circles. *Platysolenites* is a further potential producer of lower Cambrian scratch circles. McIlroy *et al.* (2001) suggested

that it may have had a life style similar to that of *Bathysiphon*, known to produce scratch circles in Miocene strata as reported by Uchman & Rattazzi (2013). Both *Ladatheca* and *Platysolenites* have been reported from the Breidvika Formation (McIlroy & Brasier 2017, McIlroy *et al.* 2001) but the Manndrapselva Member scratch circles do not contain morphological features that reveal producer identity. The Vingerbreek Member in Namibia and South Africa yields tubular fossils of unknown ecology (Cohen *et al.* 2009, Almond pers. obs.) while occurrences of scratch circles in the Vingerbreek Member in South Africa are associated with abundant carbonaceous filamentous fossils that are probable vendotaenids. Again, the life style of these organisms is poorly known.

The oldest undoubted scratch circles are found in late Ediacaran rocks (Table 1). Possibly earlier scratch circles may be present in the early Neoproterozoic (Zhang *et al.* 2016) Changlinzi Formation of northern China. These were first interpreted as Ediacara-type fossils (Xing & Liu 1979), and later as structures of inorganic origin formed through fluid escape (Chen 1984, Sun 1986). Features such as concentric ridges and development on several successive laminae is consistent with an origin as scratch circles, but this needs further consideration. As noted by Knoll & Xiao (2003) scratch circles could provide evidence for early rooted or attached organisms, such as algae or metazoans, even where these are not otherwise preserved. The apparent absence of scratch circles in pre-Ediacaran rocks could therefore be of evolutionary significance.

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Figure Captions

Figure 1. Modern (A, B) and fossil (C–F) scratch circles. A, B – Scratch circles from Bornholm, Denmark, formed by grass on sand dunes. Scale bar in A is 10 cm, in B 5 cm. C –

Flag scratch circles from the Triassic Karlstadt Formation, Förderstedt, Saxony-Anhalt, Germany. A wider view of the slab with additional scratch circles is posted at www.steinkern.de/steinkern-de-galerie/sachsen-anhalt/scharrkreise-14102. Material in collection of Jens Wiedenbeck. Scale bar is 5 mm. D – Scratch circles preserved in negative epirelief from the middle Triassic Gilsdorf Formation, northwestern Trier Embayment, Germany. Previously described in Kellner (1995). . Scale bar is 10 mm. E – The “holotype” of *Kullingia concentrica*, Torneträsk Formation, lower Cambrian, northern Sweden. Scale bar is 10 mm. Sveriges Geologiska Undersökning (Uppsala) Type 22. F – Torneträsk Formation scratch circles with preserved imprint of the scratch circle-forming organism. Scale bar is 10 mm. Sveriges Geologiska Undersökning (Uppsala) 30887 Cn1. Image credits: Dirk Knaust (A, B); Jens Wiedenbeck (C); Doris Dittrich (D).

Figure 2. Reproductions of figures 3 and 4 of Nathorst (1886) with comparison of a structure from the lower Cambrian Mickwitzia sandstone (left) with modern scratches made by a plant in sand. This is possibly the earliest published identification of a fossil scratch circle.

Figure 3. The here preferred and alternative (in parenthesis) terminology applied to scratch circles. In hyporelief preservation scratch circles consist of ridges with, or without, a pimple or knob at the centre of curvature.

Figure 4. A – Location of the Digermulen Peninsula in Arctic Norway. Also indicated is location of Lake Torneträsk, northern Sweden. B – Map showing location and geological setting (based on Siedlecka *et al.* 2006) of scratch circles in the Manndrapselva Member. C – Simplified stratigraphical profile of the Manndrapselva Member. Placement of boundary

between Manndrapselva Member and Breidvika Formation follows Banks (1971, vol.1, p. 82).

Figure 5. Scratch circles from the Stáhpogieddi Formation, Digermulen Peninsula, Arctic Norway. A – Partially preserved specimen on bed sole with sharp delicate ridges from the third cycle of Manndrapselva Member, along the Manndrapselva river. Scale bar is 5 mm. TSGf 18397. B – Rubber peel of scratch circle preserved in negative epirelief from coastal exposures of the third cycle of Manndrapselva Member. Scale bar is 5 mm. TSGf 18398. C – Base of thin sandstone bed from first cycle of Manndrapselva Member, along the Manndrapselva river, with several flag scratch circles. Scale bar is 10 mm. TSGf 18399. D – Possible large scratch circle from coastal exposures of the lower part of Indreelva Member. Note deflected ridges in lower left portion of image. Scale bar is 30 mm. TSGf 18400. All samples are housed at the Tromsø University Museum.

Figure 6. Scratch circle-yielding coastal outcrop of Manndrapselva Member. A – Outcrop and stratigraphical location of scratch circle (SC; Fig. 5B), *Gyrolithes* isp. (G; Fig. 6B), and *Treptichnus pedum* (TP; Fig. 6C) from the lower part of third cycle (Ma3) of Manndrapselva Member. Light-coloured sandstone to lower left marks top of second cycle (Ma2). According to Banks (1971, vol. 1, p. 68) a fault downthrows strata to the right (NE) of the ravine by 6–7 m. Strata in upper part of image belong to Lower Member of Breidvika Formation (Br). Height of visible section approximately 35 m. B – Bed sole with several specimens of the vertically oriented spirally coiled trace fossil *Gyrolithes* isp. Field photo. Scale bar is 5 mm. C – Bed sole with *Treptichnus pedum*. Field photo. Scale bar is 10 mm.

Figure 7. Geological and stratigraphic context of late Ediacaran scratch circles from Namibia and South Africa. A – General outline of the Nama foreland basin with sub-basins delineated by topographic highs (based on Germs & Gresse 1991). Location of scratch circles in Vioolsdrif area, south of Orange River, is indicated by star associated with 1. Location of scratch circles in Farm Swartpunt, southern Namibia is indicated by a star associated with 2. B – Simplified representation of Nama Group stratigraphy (based on Germs & Gaucher 2012), with position of scratch circles in the Vingerbreek and Spitskop members. Radiometric ages are based on Schmitz (2012).

Figure 8. Outcrop image (from Almond 2009) of the Nudaus and lower Urusis formations at Neint Nababeep Plateau, south of Vioolsdrif, to the north of scratch circle locality. From base to top are seen the reddish-brown Niederhagen Member (NH) with quartzite channels, pale weathered shale of the Vingerbreek Member (VB) with intermittent resistant-weathering units of sandstone or quartzite, a thin black limestone marker in the upper Vingerbreek Member (vc), the quartzite-dominated Nasep Member (NS), and the thick black limestone of the Huns Member (HM). Approximate stratigraphic horizons of scratch circle specimens in Figure 9 are arrowed. Thickness of Vingerbreek Member 182 m.

Figure 9. Scratch circles from the Vingerbreek Member, Nudaus Formation, northern Republic of South Africa. A, B – Scratch circle shown with different directions of low angle light. Scale bar is 10 mm. SAM-PT-022511. C – Partially preserved overlapping scratch circles. Scale bar is 20 mm. SAM-PT-022512. All samples are housed at Iziko South African Museum, Cape Town.

Figure 10. Scratch circle from the Spitskop Member at Farm Swartpunt, southern Namibia. A – View of block with scratch circle (upper right-hand side) and prominent tool marks, some probably attributed to *Swartpuntia*. Field photo. Scale bar is 50 mm. B – Flag scratch circle with sharp ridges and possible impression of tubular organism at the centre of curvature. Scale bar is 10 mm.

Table 1. List of reports of scratch circle in the geological record. An asterisk indicates that