

# Deep-water trace fossils in the Ilfjellet rift basin (Middle Ordovician), central Norwegian Caledonides

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## Abstract

The late Early to early Middle Ordovician Fjellvollen Formation, Central Norwegian Caledonides, is a part of the Ilfjellet Group volcano-sedimentary succession formed in a rift basin that opened along the Laurentian margin. Depositional facies and trace fossils indicate the *Nereites* ichnofacies, typically found in distal turbidites and deep marine deposits. The recovered trace fossils include *Alcyonidiopsis*, *Chondrites*, *Dictyodora*, *Gordia*, *Helminthoidichnites*, *Macaronichnus*, *Monomorphichnus*, *Nereites*, *Oikobesalon*, *Palaeophycus*, *Protovirgularia* and *Treptichnus*. No body-fossils have been reported from the Fjellvollen Formation, but the trace fossils indicate the presence of varied epi- and infaunas of arthropods, bivalves, gastropods and polychaets. The abundance of meandering and looping trace fossils is comparable to what is found in the inferrably time-equivalent Vuddudalen Group farther north, although lack of graphoglyptids like *Megagraption* in the Fjellvollen Formation may indicate more proximal, unstable depositional conditions in fan-fringe and adjacent basin-plain settings.

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**Keywords:** Trace fossils; *Nereites* ichnofacies; Ordovician; Ilfjellet Group; Caledonides; Central Norway

## 1. Introduction

Since the pioneering work in the late 1800s (Kjerulf, 1871, 1875; Reusch, 1890; Törnebohm, 1896), the Trondheim Nappe Complex of the central Norwegian Caledonides has been extensively studied, with focus on the fragmented ophiolite assemblages, the overlying complex series of volcanic and sedimentary rocks, and the prolific fauna found in the Hølanda–Horg area, southwest of Trondheim (e.g., Vogt, 1945; Grenne and Roberts, 1998; Slagstad et al., 2014; Fig. 1A, B). Following the most recent tectonostratigraphic model by Gasser et al. (2022), the Furongian/Early Ordovician ophiolite fragments are overlain by two contrasting time-equivalent, Early to Mid-

dle Ordovician volcano-sedimentary groups: (1) the proximal, shallow-water, fossil-rich shelf deposits of the Hølanda Group including the shoshonitic Hølanda Porphyrites (Grenne and Roberts, 1998), and (2) the distal, deep-water, turbiditic deposits of the Ilfjellet Group, including extensive MORB-basalts (Gasser et al., 2022; Fig. 1B). The Ilfjellet basin is interpreted to have formed in a rift basin that opened along the Laurentian margin as a result of slab rollback subsequent to arc–continent collision, ophiolite obduction and subduction polarity flip (Gasser et al., 2022).

The Ilfjellet Group consists of (1) the turbiditic Klæbu Formation unconformably overlying the Vassfjellet ophiolite, (2) the basalt-dominated Jonsvatnet Formation (including the former Jonsvatnet Greenstone Formation; Grenne and Roberts, 1983), (3) the basalt-dominated Mostadmarka Formation (former Støren Group s.s.; e.g.,

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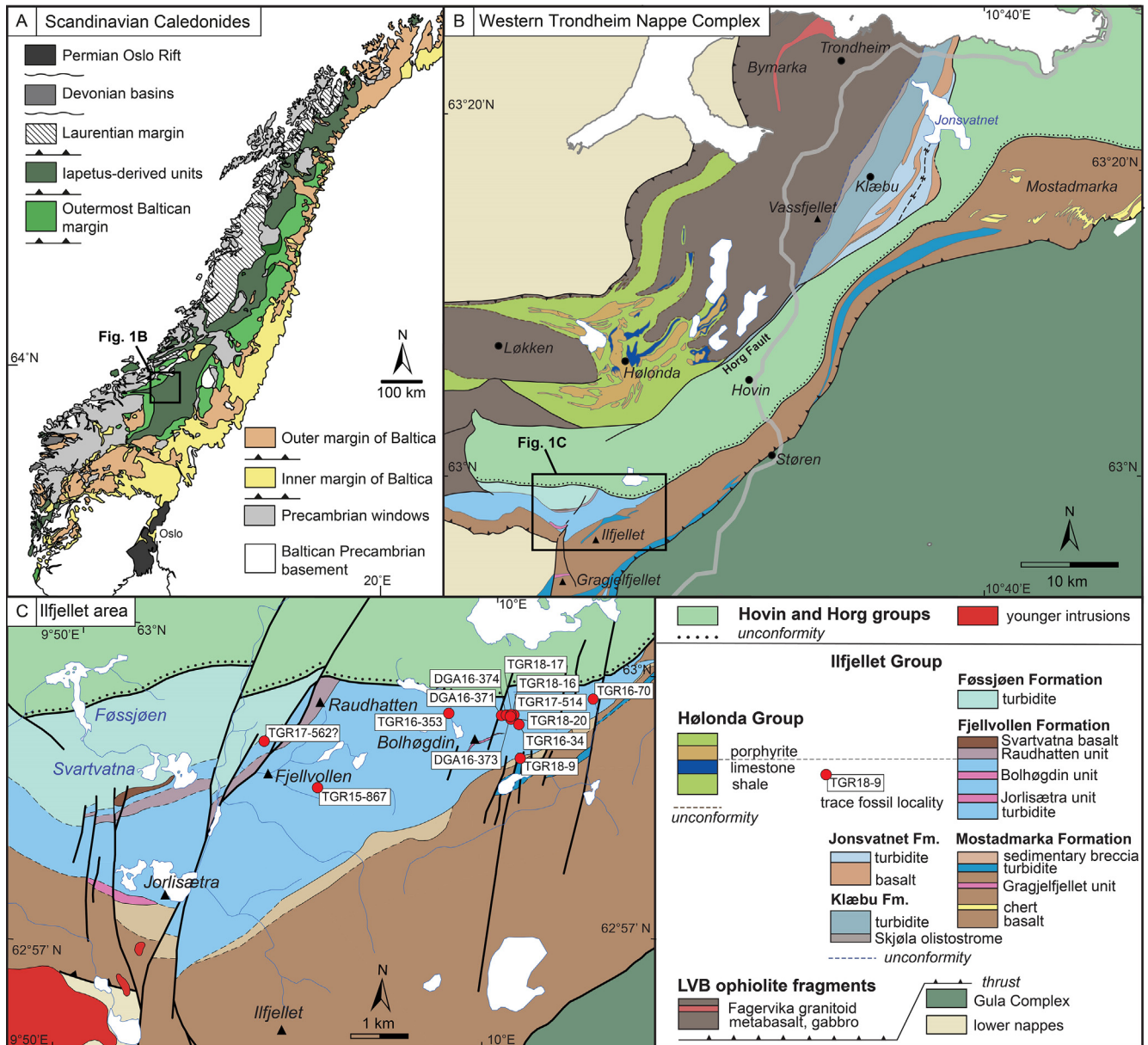


Fig. 1. Geological overview maps. (A) Simplified tectonic map of the Scandinavian Caledonides. (B) Geological map of the western Trondheim Nappe Complex, with the distribution of the Hølanda and Ilfjellet groups indicated after Gasser et al. (2022). (C) Geological map of the Ilfjellet area, with localities of recovered trace fossils within the Fjellvollen Formation.

Grenne et al., 1999), (4) the sediment-dominated Fjellvollen Formation, and (5) the sediment-dominated Føssjøen Formation (Fig. 1B; Gasser et al., 2022). In particular, the Fjellvollen Formation is rich in trace fossil occurrences, but body fossils have not yet been identified.

The abundant trace fossils in the turbiditic succession of the Fjellvollen Formation were briefly mentioned in the revised lithostratigraphy outlined by Gasser et al. (2022), but detailed descriptions were not included. The lack of records of body fossils in the Fjellvollen Formation is puzzling, given the rich recoveries in the Hølanda Group. Possibly this can be related to different depositional settings, with the Fjellvollen Formation representing distal, deep-water deposits, compared to more shallow marine deposits

with richer biodiversity in the Hølanda Group. The objective of the present study is to test this hypothesis by analyzing the trace fossil assemblages recovered in the Fjellvollen Formation, and to use the trace fossils to identify variations in benthic environments and ichnofacies during deposition within the Ilfjellet rift basin.

## 2. Geological setting

The Ilfjellet Group, with the Fjellvollen Formation (Figs. 1, 2), is a complex volcano-sedimentary succession deposited unconformably on ophiolite fragments that had been obducted on or near the Laurentian margin somewhere between 479 and 475 Ma (Gasser et al., 2022). At

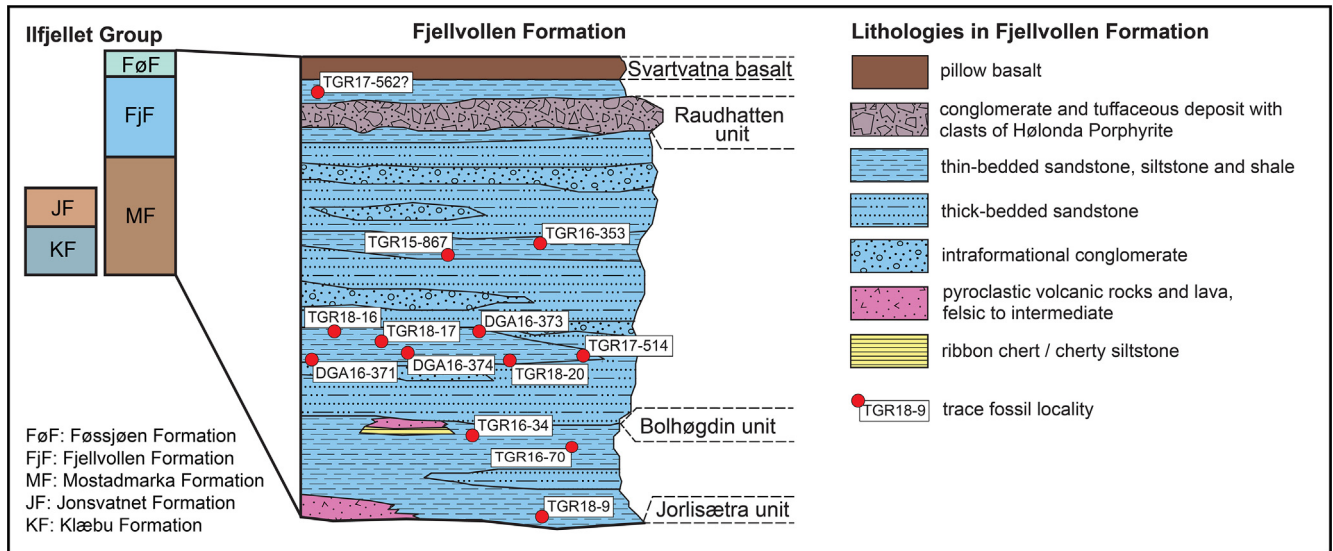


Fig. 2. Generalized lithostratigraphic sequence of the Fjellvollen Formation (based on Gasser et al., 2022), with approximate position of the recovered trace fossils.

ca. 475–463 Ma, shortly after ophiolite obduction and uplift, extensive MORB-basalts of the Jonsvatnet and Mostadmarka formations were extruded and intercalated with turbiditic deposits of the Klæbu and Fjellvollen formations (Gasser et al., 2022). Basin fill includes erosional products from Laurentia and the time-equivalent Hølonða shelf to the west.

The Fjellvollen Formation, which is the focus of the present account, has a maximum preserved thickness of around 2.3 km (Gasser et al., 2022). It consists of predominantly siliciclastic deposits, mainly distal turbidites, including thin-bedded, grayish or greenish-gray, quartz-rich and variably calcareous sandstone, conglomerate, siltstone and shale, with intercalated thin volcanic units (Figs. 2, 3). Its lower 200–500 m are characterized by thin-bedded, turbiditic siltstone and sandstone (Fig. 3), as well as the Jorlisætra and Bolhøgdin volcanic units that comprise mafic to intermediate lava and tuff (Fig. 2; Gasser et al., 2022). Ribbon chert and limestone is observed locally.

The upper part of the formation is predominantly a succession of turbiditic graywackes with thick-bedded calcareous sandstones and conglomerates, with subordinate thin-bedded silt- and shale-dominated units (Fig. 2). Complete Bouma sequences are present, and the succession shows an overall upward-coarsening, with increasing contents of carbonate (Gasser et al., 2022).

The turbiditic graywackes are overlain by the around 200 m thick Raudhatten unit, comprising very coarse conglomerate and bedded volcanoclastic deposits that include abundant clasts of Hølonða Porphyrite. These pass upwards into ca. 100 m of turbiditic, thin-bedded siltstone and shale and, ultimately, the up to 150-m-thick Svartvatna basalt unit of both pillowed and massive lavas (Fig. 2; Gasser et al., 2022). The Fjellvollen Formation is

overlain by the turbiditic Føssjøen Formation (Gasser et al., 2022).

### 3. Sample localities and materials

All trace fossils described herein are found in silt- and shale-dominated units of the Fjellvollen Formation (Figs. 1C, 2). The majority were found in ancient, small roof slate quarries (see sample locality descriptions, Table 1). One locality, TGR17-562, is interpreted to lie in the upper part of the Fjellvollen Formation based on its lithological and sedimentary characteristics; however, its exact stratigraphic position is uncertain due to fault displacements and the lack of reliable marker units like the different volcanic units in this particular area (Fig. 1C). The studied materials include field observations, photos and samples collected by Tor Grenne and Deta Gasser during bedrock mapping in the western part of the Trondheim Nappe Complex. Fourteen slabs with examined trace fossils are stored in the museum collections at NTNU Vitenskapsmuseet in Trondheim. Collection numbers of illustrated specimens/slabs are listed in the captions of Figs. 4–7. Pictures of trace fossils without collection numbers are field photos.

### 4. Systematic ichnology

?*Alcyonidiopsis* isp.  
(Fig. 4A)

**Locality:** TGR16-70.

**Description (1 specimen):** Horizontal, flattened endichnial, unbranched and coiled cylinder, 3–4 mm wide. Cylinder with sharply defined regular boundaries (walls) and filled with mud which resembles pelletal sediment.

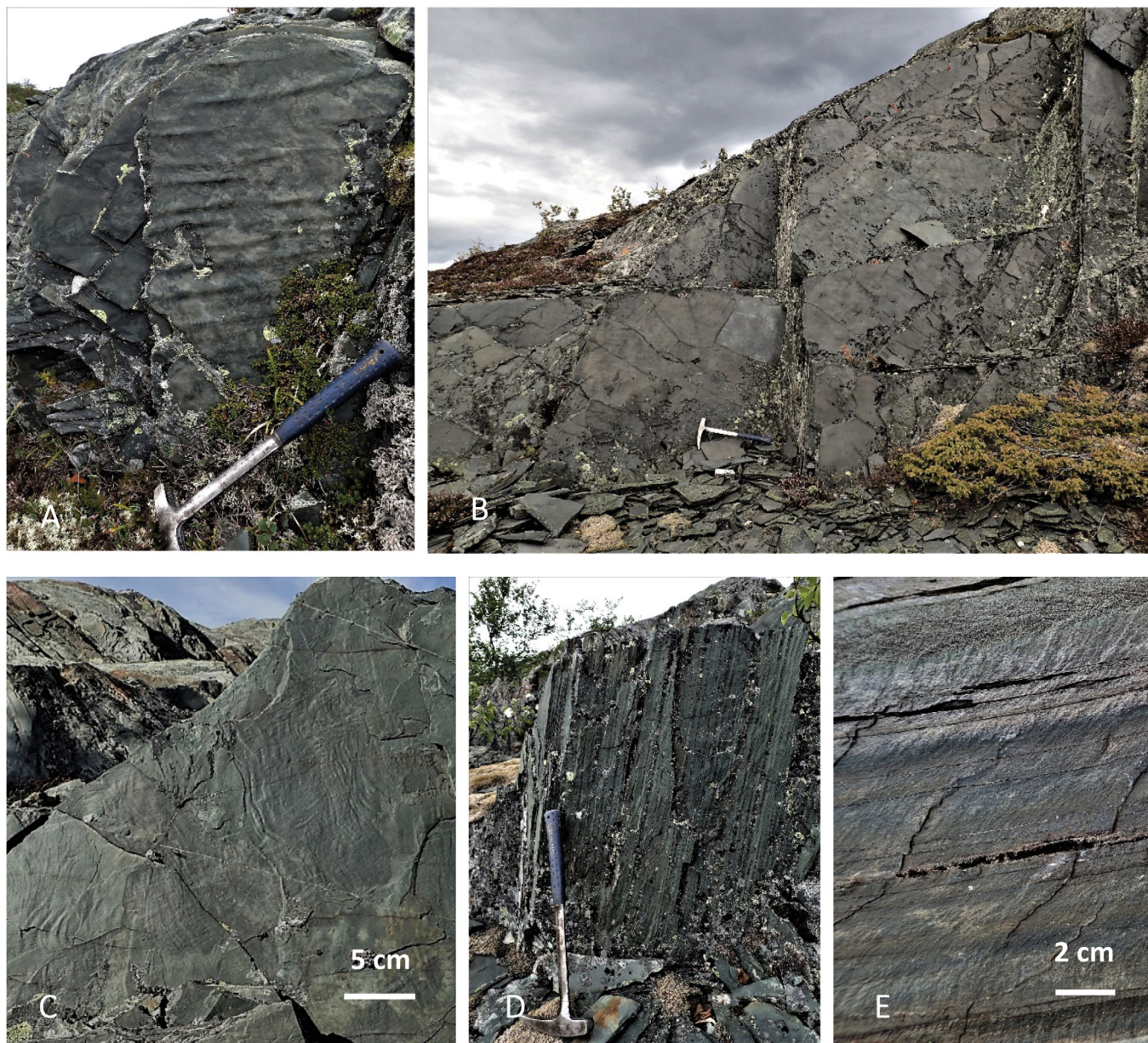


Fig. 3. Thin-bedded quartz-rich silty sandstones, siltstones and shales of the Fjellvollen Formation. (A) Small-scale ripples at locality TGR16-353. (B) Shale at locality TGR17-514. (C) Shale with small ripples and trace fossils at locality TGR18-16. (D) Bedded shale at locality TGR18-16. (E) Laminated deposits at locality TGR16-70. Hammer (40 cm) for scale in (A, B, D).

**Interpretation:** The ichnogenus *Alcyonidiopsis* is interpreted as feeding burrow of polychaetes.

**Remarks:** The single form here recorded as *?Alcyonidiopsis* isp. differs from typical straight and curved to slightly irregular *Alcyonidiopsis* isp. (Pickerill and Narbonne, 1995; Uchman, 2001; Uchman et al., 2005) by its coiled shape and less well-preserved fecal pellets within the cylinder.

*Alcyonidiopsis* isp. has been recorded from different environments, from lacustrine (Metz, 2015) to shallow marine (Buatois and Mángano, 2012) and deep marine/bathyal settings (Uchman et al., 2005). *Alcyonidiopsis* is known from the Cambrian to the Miocene (Uchman, 2001; Uchman et al., 2005; Mángano and Buatoise, 2016).

*Chondrites* isp.  
(Fig. 4B)

**Locality:** TGR17-562.

**Description (3 specimens):** Vertical shafts branching into lateral, oblique and horizontal, burrows. The burrow diameter is 1–2 mm, with branches less than 1 mm in thickness. The branches spread in a radiating structure.

**Interpretation:** *Chondrites* is interpreted as an infaunal deposits feeder, but the producers of this ichnogenus are unknown (Uchman et al., 2005).

**Remarks:** *Chondrites* isp. is mostly known from fully marine settings, but is also known from restricted/dysaerobic,

Table 1

Locality numbers, geographic positions of localities, geographic areas and listing of ichnotaxa recovered in the Fjellvollen Formation. Note: Coordinates (East - North) are in UTM32 (EUREF89).

Locality	Coordinates	Areas	Comments	Trace fossils
DGA16-371	550470 - 6984860	Skjetna		<i>Dictyodora</i> cf. <i>tenuis</i>
DGA16-373	550715 - 6984932	Liatjønna	Quarry	? <i>Curvolithus</i> isp., <i>Helminthoidichnites tenuis</i> , <i>Treptichnus</i> isp., <i>Dictyodora</i> cf. <i>tenuis</i> , <i>Gordia</i> isp.
DGA16-374	550666 - 6984886	Liatjønna	Quarry	? <i>Curvolithus</i> isp., <i>Dictyodora</i> cf. <i>tenuis</i> , <i>Gordia</i> isp., <i>Helminthoidichnites tenuis</i> , <i>Monomorphichnus</i> isp., <i>Protovirgularia dichotoma</i> , <i>Nereites missouriensis</i>
TGR15-867	547188 - 6983659	Langdalen		<i>Helminthoidichnites tenuis</i>
TGR16-34	550870 - 6984722	Holtjønna		? <i>Phycodes</i> isp.
TGR16-70	552059 - 6985339	Ljøsåa	Quarry	? <i>Curvolithus</i> isp., <i>Dictyodora</i> cf. <i>tenuis</i> , <i>Gordia</i> isp., <i>Monomorphichnus</i> isp., <i>Protovirgularia dichotoma</i>
TGR16-353	549602 - 6984981	Stentjønna		<i>Gordia</i> isp., <i>Palaeophycus</i> isp.
TGR17-514	550919 - 6984904	Liatjønna	Quarry	<i>Dictyodora</i> cf. <i>tenuis</i> , <i>Gordia</i> isp.
TGR17-562	546580 - 6985226	Raudhattjønna	Quarry	<i>Chondrites</i> isp., <i>Gordia</i> isp., <i>Macronichnus</i> isp., <i>Oikobesalon</i> isp., aff. <i>Psammichnites</i> isp.
TGR18-9	550799 - 6984168	Svarttjønna		<i>Helminthoidichnites tenuis</i>
TGR18-16	550550 - 6984943	Liatjønna	Quarry	<i>Gordia</i> isp.
TGR18-17	550589 - 6984922	Liatjønna		? <i>Curvolithus</i> isp., <i>Gordia</i> isp., <i>Palaeophycus</i> isp.
TGR18-20	550806 - 6984881	Liatjønna	Quarry	<i>Helminthoidichnites tenuis</i>

low-diversity environments (Bromley and Ekdale, 1984; Seilacher, 1990; Gérard and Bromley, 2008). *Chondrites* are classified as chemichnion trace fossils (Bromley, 1996). The stratigraphic range is Precambrian to Holocene (Uchman et al., 2005; Buatois et al., 2020).

?*Curvolithus* isp.  
(Figs. 4B, 6C)

**Locality:** DGA16-373, DGA16-374, TGR16-70, TGR18-17.

**Description (8 specimens):** Endichnial, horizontal to oblique, straight or slightly curved burrows, with poorly developed trilobate upper surface preserved on the bedding plane. The central lobe is wider than the marginal ones. Total width of the burrows is 8–12 mm.

**Interpretation:** *Curvolithus* is interpreted as a locomotion trace (Repichnia) of possibly gastropods, flatworms, or nemertean (Buatois et al., 1998).

**Remarks:** *Curvolithus* is known from Precambrian to Miocene, and is found in estuarine and deltaic to marine, offshore environments (Buatois et al., 1998; López-Cabrera et al., 2008; Gayakvad and Solanki, 2021).

*Dictyodora* cf. *tenuis* sensu Uchman et al. (2005)  
(Figs. 4B, E, 6A, D, 7A)

**Locality:** DGA16-371, DGA16-373, DGA16-374, TGR16-70, TGR17-514, TGR18-19.

**Description (7 specimens):** Narrow burrows, forming two-order meanders on parting bedrock surfaces (from Uchman et al., 2005). The meandering borrows crosscut each other and some show fine-grained, c-shaped, fillings.

The width of the narrow burrows is 2–3 mm, and the width of broader burrows is 12–15 mm.

**Interpretation:** Pazos et al. (2015) suggested that *Dictyodora* could be made from feeding activities rather than respiration, but the tracemaker is not documented.

**Remarks:** The ichno-genus *Dictyodora* is reported from the Early Cambrian to Permian, mainly in deep water turbidity flow deposits (Uchman et al., 2005; Zhang et al., 2020).

*Gordia* isp. sensu Uchman et al. (2005)  
(Figs. 6C, 7B)

**Locality:** DGA16-373, DGA16-374, TGR16-70, TGR16-353, TGR17-514, TGR17-562, TGR18-17.

**Description (15 specimens):** Hypichnial, thin, smooth, meandering and looping ridges preserved in semi-relief (from Uchman et al., 2005).

**Interpretation:** *Gordia* can be interpreted as locomotion trails (repichnia) or feeding traces (pascichnia) produced by various organisms, including fresh-water insect larvae and shallow and deep-marine gastropods and Annelida (Fillion and Pickerill, 1990; Gaigalas and Uchman, 2004; Rodríguez-Tovar et al., 2014).

**Remarks:** *Gordia* is known from different facies and settings in non-marine and marine environments (Pickerill et al., 1984; Gaigalas and Uchman, 2004). The specimens recorded from the Fjellvollen Formation appear similar to the ones described from Ordovician turbiditic sandstone of the Vuddudalen Group farther north (Uchman et al., 2005; Henriksen et al., 2018; Roberts et al., 2019) and Ordovician flysch deposits in Wales (McCann, 1990).

*Helminthoidichnites tenuis* Fitch, 1850  
(Fig. 4C)

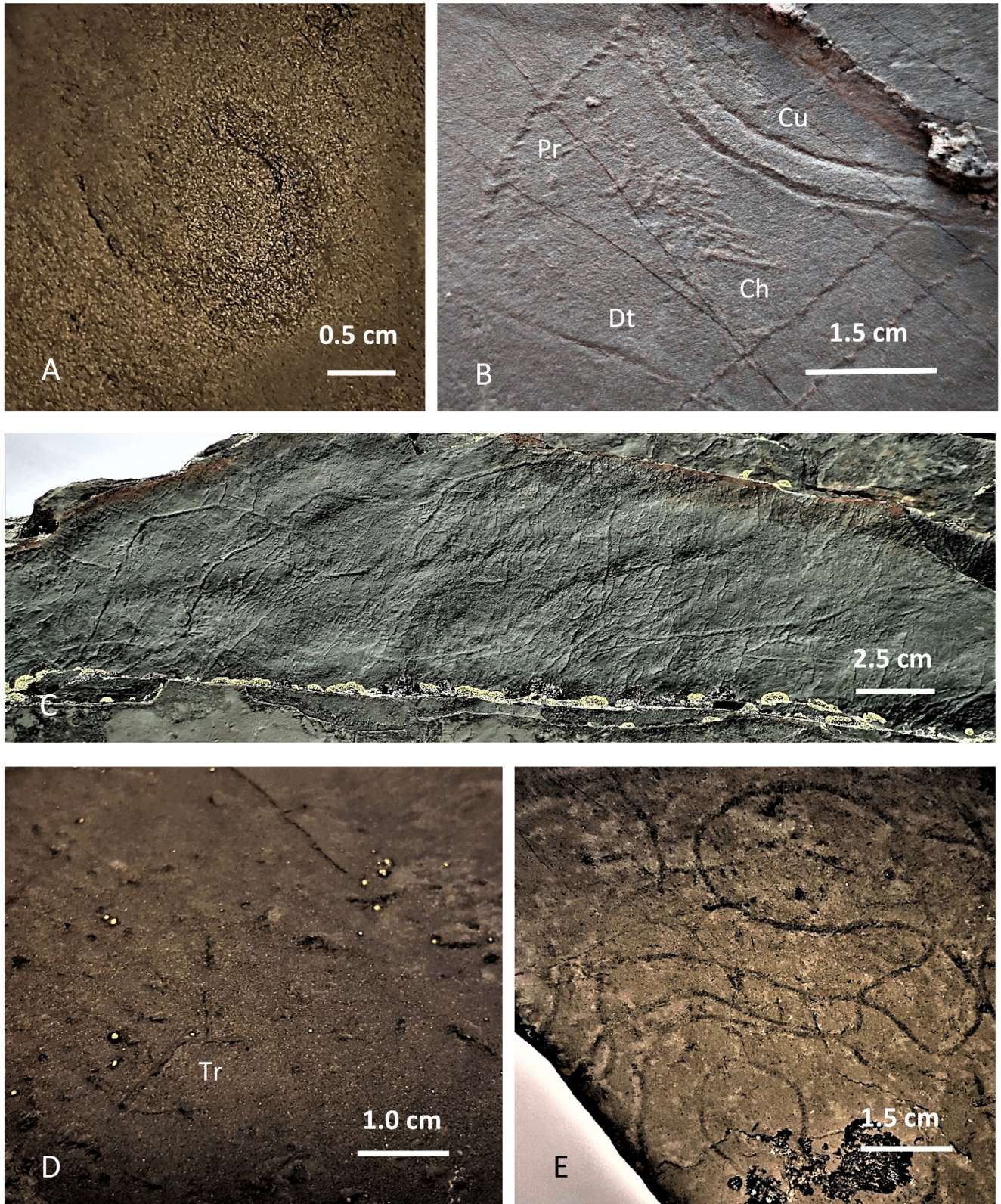


Fig. 4. Trace fossils from the Fjellvollen Formation. (A) *?Alcyonidiopsis* isp. (locality TGR16-70; NTNU VM Collection no. 10018). (B) *?Curvolithus* isp. (Cu), *Dictyodora* cf. *tenuis* (Dt), *Chondrites* isp. (Ch) and *Protovirgularia dichotoma* (Pr) (locality DGA16-374; NTNU VM Collection no. 10017). (C) *Helminthoidichnites tenuis* (locality TGR15-867). (D) *Treptichnus* isp. (Tr) (locality DGA16 373A; NTNU VM Collection no. 10011). (E) *Dictyodora* cf. *tenuis* (locality DGA16 373B; NTNU VM Collection no. 10012).

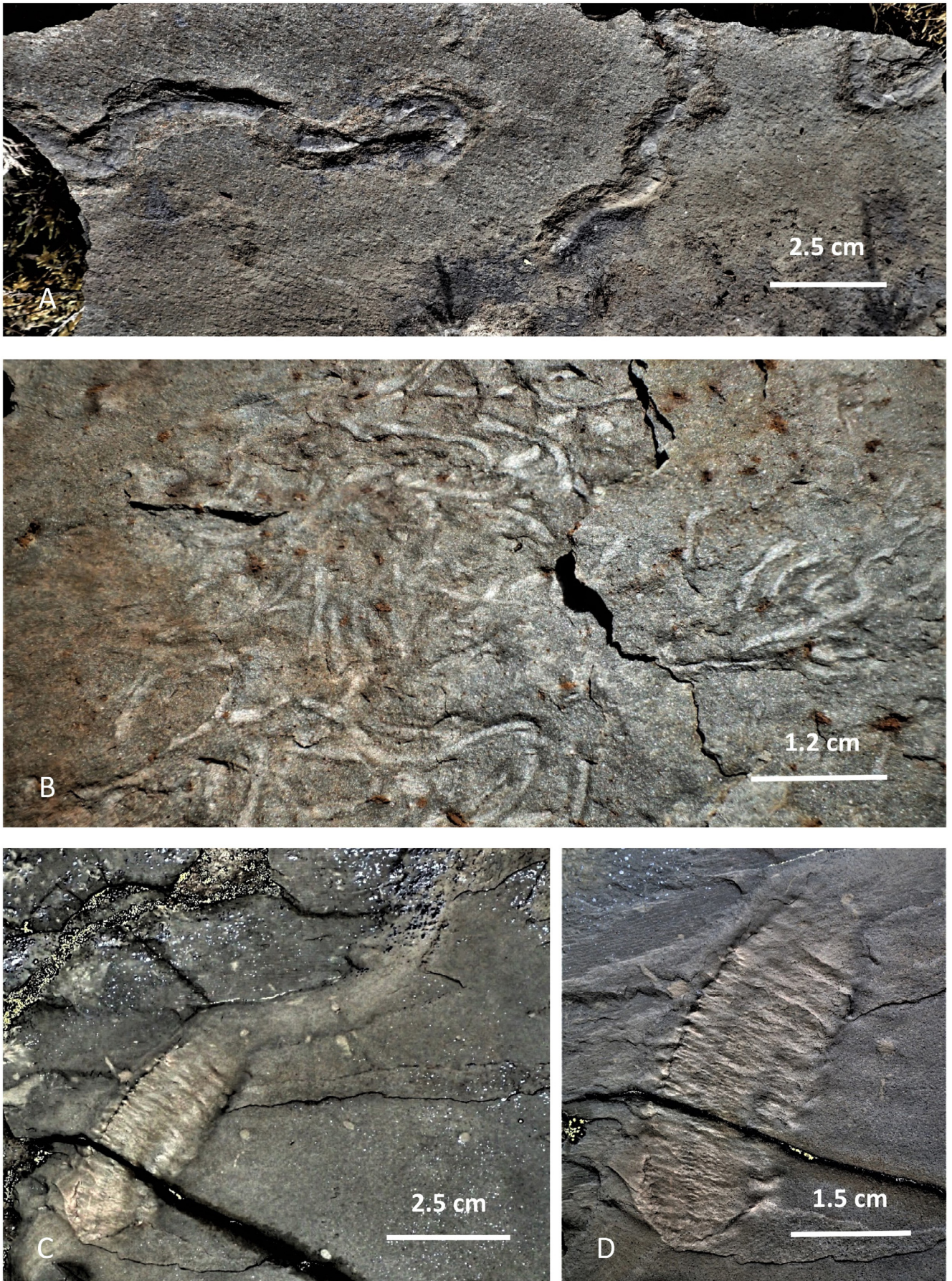


Fig. 5. Trace fossils of the Fjellvollen Formation. (A) aff. *Psammichnites* isp. (locality TGR17-562; NTNU VM Collection no. 10024). (B) *Macaronichnus* isp. (locality TGR17-562; NTNU VM Collection no. 10022). (C, D) *Oikobesalon* isp. (locality TGR17-562).

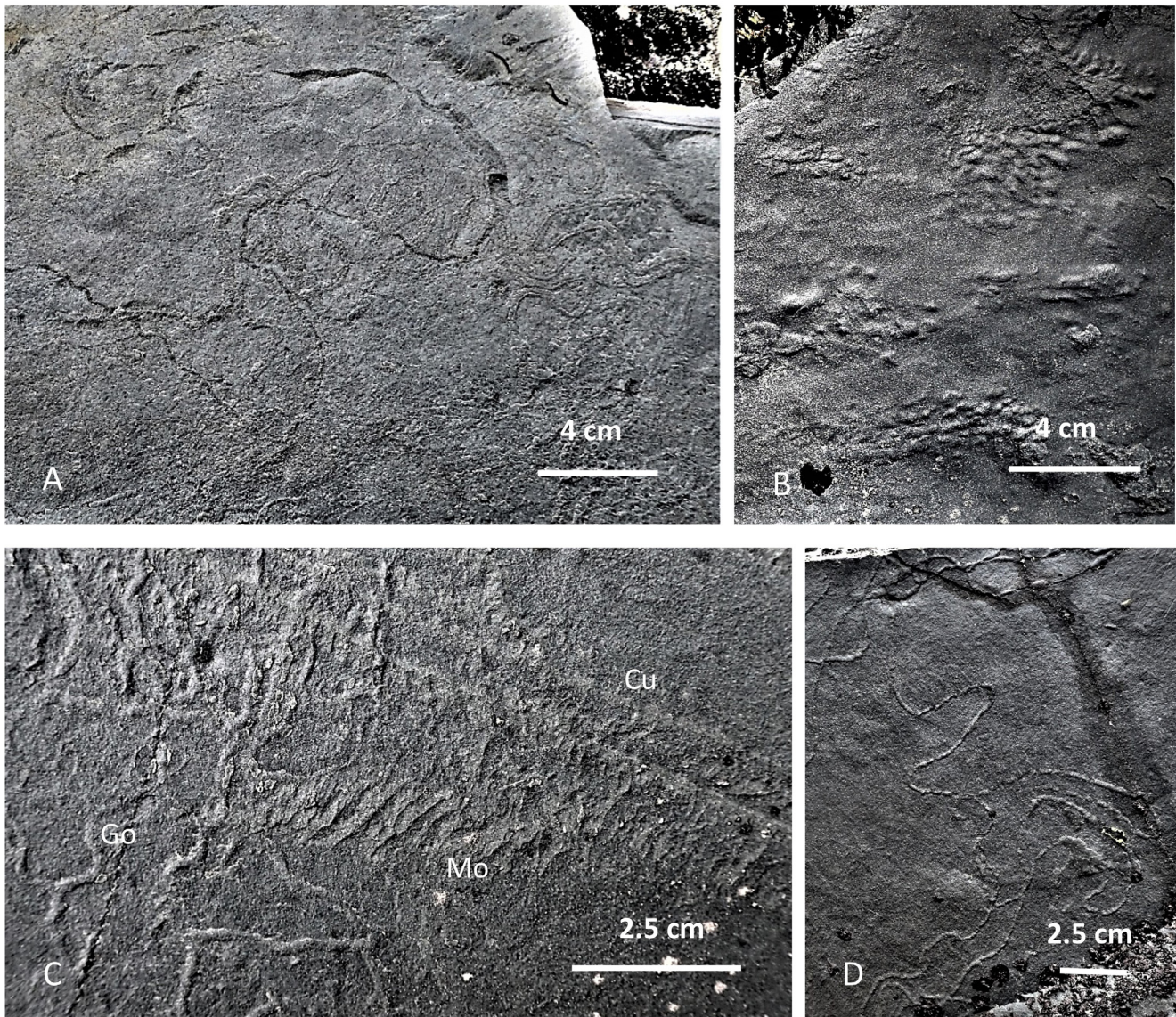


Fig. 6. Trace fossils of the Fjellvollen Formation. (A) *Dictyodora* cf. *tenuis* (locality DGA16-371). (B) *Nereites missouriensis* (locality TGR18-18). (C) ? *Curvolithus* isp. (Cu), *Gordia* isp. (Go) and *Monomorphichnus* isp. (Mo) (locality DGA16 374; NTNU VM Collection no. 10013). (D) *Dictyodora* cf. *tenuis* (locality TGR18-20).

**Locality:** DGA16-373, DGA16-374, TGR15-867, TGR18-20.

**Description (5 specimens):** Epichnial and hypichnial, simple, unbranched, cylindrical horizontal winding tracks on parting surfaces, with irregular meanders and loops, occasionally overlapping, 1–2 mm wide and of variable length.

**Interpretation:** Tracks assigned to *Helminthoidichnites tenuis* can be produced by different animals inhabiting various non-marine to marine environments (Uchman et al., 2005; Demircan and Uchman, 2017a, 2017b). Buatois et al. (1998) interpreted this ichnotaxon as a grazing trace (pascichnion), most likely produced by vermiform animals.

**Remarks:** Various species of the ichno-genus *Helminthoidichnites* are known from the Precambrian to Pleistocene (Demircan and Uchman, 2017b).

*Macaronichnus* isp.  
(Fig. 5B)

**Locality:** TGR17-562.

**Description (23 specimens):** Densely packed, thin sub-vertical to sub-horizontal cylindrical smooth-sided burrows with circular cross section. Longitudinally straight, or slightly curved to sinuous, not branched, but with common interpenetrations and occasional false branching. There is marked segregation between the light-colored mineral infill in the circular burrows and the darker colored surrounding sediments (after Clifton and Thompson, 1978; Rodríguez-Tovar and Aguirre, 2014). In the present materials diameters of the burrows are uniform and ~1 mm. The burrows are up to 15 mm in length.



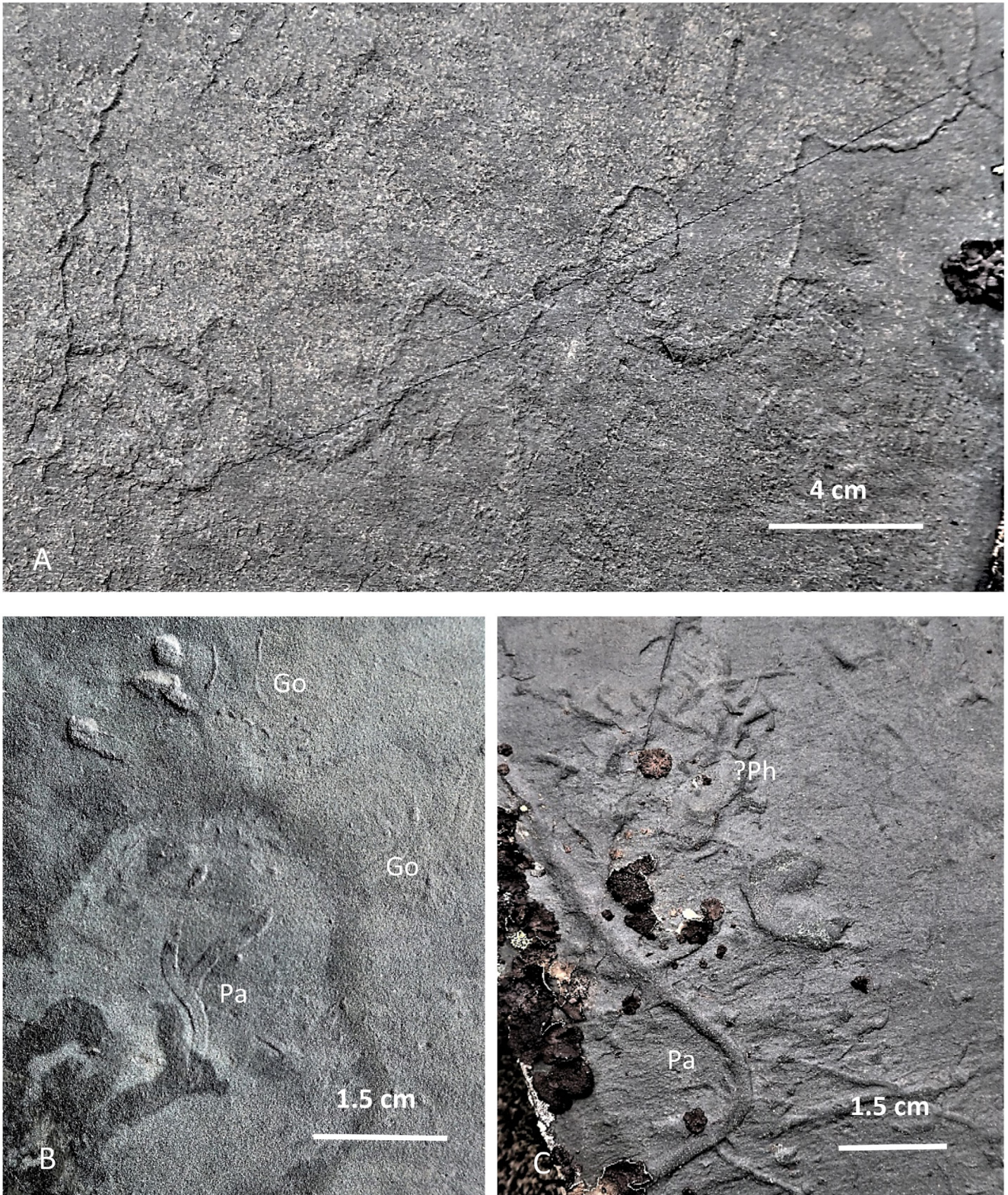


Fig. 7. Trace fossils of the Fjellvollen Formation. (A) *Dictyodora* cf. *tenuis* (locality DGA16-371). (B) *Gordia* isp. (Go) and *Palaeophycus* isp. (Pa) (locality TGR16-353). (C) *Palaeophycus* isp. (Pa) and ?*Phycodes* isp. (?Ph) (locality TGR16-34).

**Interpretation:** *Macaronichnus* has been described as traces of polychaete worms feeding on bacteria and organic matter on the surface of sand grains (Clifton and Thompson, 1978; Miguez-Salas et al., 2020).

**Remarks:** Most records of *Macaronichnus* are from shallow-marine, mainly foreshore environments, but the ichnogenus has also been reported from deep-marine contourites (Miguez-Salas et al., 2020; Seike et al., 2011). In

general, traces of *Macaronichnus* are larger (i.e., diameter of 2–17 mm) than those recorded in the Fjellvoll Formation (diameter around 1 mm). In his study of Cambro-Ordovician trace fossils from the southwestern Norwegian Caledonides, Knaust (2004) found that the size of *M. segregatis* is variable and ranges from 2 to 4 mm in diameter, although smaller burrows were also observed. *Macaronichnus* is known from Cambrian to Modern times (Knaust, 2004; Seike et al., 2011).

*Monomorphichnus* isp.  
(Fig. 6C)

**Locality:** DGA16-374, TGR17-70, TGR16-70.

**Description (5 specimens):** *Monomorphichnus* isp. comprises series of isolated, slightly curved ridges repeated laterally, moderately spaced from each other; ridges vary from 10 to 15 mm in length and 1 to 2 mm in width. The distance between the ridges is 2–3 mm.

**Interpretation:** *Monomorphichnus* has been interpreted as arthropod tracks (Jensen and Mens, 2001).

**Remarks:** *Monomorphichnus*, with its clusters of striations, is somewhat similar or even conspecific to *Dimorphichnus* which consists of a row of elongate striations and a parallel row of shorter striations. Mángano et al. (2005), however, suggested that *Monomorphichnus* should be retained, at least pending a full revision. *Monomorphichnus* isp. is known from the Early Cambrian to Early Permian (Jensen and Mens, 2001; Minter and Lucas, 2009; Tiwari et al., 2013).

*Nereites missouriensis* Weller, 1899  
(Fig. 6B)

**Locality:** DGA16-374.

**Description (5 specimens):** Meandering, double and triple packed rows of closely packed pustules on parting surfaces and bedding planes (after Uchman et al., 2005).

**Interpretation:** It has been described as locomotion traces of annelid worms (Seilacher, 2007), but according to more recent records *Nereites* is a typical pascichnion produced by an unknown tracemaker (Hovikoski et al., 2019).

**Remarks:** The present record comprises ichnospecies similar to *Neonereites biserialis* (Seilacher, 1960) and *Neonereites multiserialis* (Pickerill and Harland, 1988). As for comparable specimens recorded elsewhere in northern and central parts of the Trondheim Region by Uchman et al. (2005), the present specimens are assigned to ichnospecies *Nereites missouriensis*. *Nereites* is found in various marine environments; from shoreface delta-fronts to offshore deep-sea basins (Gérard and Bromley, 2008).

*Oikobesalon* isp.  
(Fig. 5C, D)

**Locality:** TGR17-562.

**Description (1 specimen):** Horizontal, unbranched, elongate burrow, up to 2 cm wide and with thin transverse fusiform, symmetrically perpendicular arranged bands. The bands are filled with fine-grained and light-coloured sediments.

**Interpretation:** Worm-like organisms, possibly polychaetes are most likely originators (Thomas and Smith, 1998).

**Remarks:** *Oikobesalon* is known from Cambrian to Silurian (Thomas and Smith, 1998; Vinn and Toom, 2014). Vinn and Toom (2014) suggested that in the Cambrian and Ordovician, *Oikobesalon* occurred in cold to temperate seas.

*Palaeophycus* isp.  
(Fig. 7B, C)

**Locality:** TGR16-353, TGR18-17.

**Description (5 specimens):** Horizontal to oblique burrows, forming sub-horizontal low ridges, or cylinders preserved in reliefs on the bedding plane. The wall-linings are of variable thickness. Specimens in the present material are not branched. The borrows contain fills similar to the host sediment. Width is from 5 to 10 mm, the length of the recorded specimens varies from 7 to 15 cm.

**Interpretation:** According to Fillion (1989) *Palaeophycus* represents dwelling (domichnia) or feeding (fodinichnia) traces of mobile, worm-like animals such as annelids. Recent records show that *Palaeophycus* are known to be produced by several animals, varying from non- and semi-aquatic insects (beetles, orthopters and hemipterans) to marine predaceous polychaetes (Krapovickas et al., 2010; Díez-Canseco et al., 2016).

**Remarks:** *Palaeophycus* is known from Precambrian to Recent (Uchman et al., 2005).

?*Phycodes* isp.  
(Fig. 7C)

**Locality:** TGR16-34.

**Description (3 specimens):** The traces here questionably assigned *Phycodes* are horizontally bundled burrows preserved outwardly as convex hyporeliefs on the bedding plane. They comprise of short, linear branches, resembling poorly preserved spreite structure that taper distally into free branches.

**Interpretation:** Most documented ichnospecies of *Phycodes* are interpreted to have been formed by worm-like organisms or possibly arthropods (Han and Pickerill, 1994).

**Remarks:** *Phycodes* is known as a marine eurybathic ichnospecies and is recorded in different marine environments from Paleozoic to Recent (Buatois et al., 2020).

*Protovirgularia dichotoma* McCoy, 1850  
(Fig. 4B)

**Locality:** DGA16-374, TGR16-70, TGR16-70.

**Description (2 specimens):** Horizontal keel-like ichnofossils, composed of invaginated cones or V-shaped marks oriented in one direction. The ribs are arranged in chevron-shaped, biserial pattern along external or internal dorsal part. In cross-section the tracks are almond-shaped or triangular in outline (after Uchman, 1998; Uchman et al., 2005).

**Interpretation:** *Protovirgularia dichotoma* are interpreted as locomotion tracks produced by bivalves (Han and Pickerill, 1994; Seilacher and Seilacher, 1994), generally associated with deposit-feeding Protobranchia (Bromley et al., 2003). Gibert and Domènech (2008) suggested that *Protovirgularia* was most likely a nuculacean, as these bivalves are actively mobile deposits-feeders, while other protobranchs are less active.

**Remarks:** While Han and Pickrill's (1994) description of *Protovirgularia* was restricted to keel-like ichnofossils covered with chevron markings opening in one direction, Seilacher and Seilacher (1994) included full-relief trace fossils described under different ichnogenera (Uchman et al., 2005). Gibert and Domènech (2008) described three morphotypes of *Protovirgularia*. The present materials include specimens resembling morphotypes 1 and 2. *Protovirgularia* is described from a wide range of depositional environments, from non-marine lacustrine (Kim et al., 2000) to deep-sea through settings (Nara and Ikari, 2011).

aff. *Psammichnites* isp.  
(Fig. 5A)

**Locality:** TGR17-562.

**Description (3 specimens):** Epichnial semi-circular looping furrow, partly bounded by levees. The loops are 3–5 mm wide and the levees 1–2 mm wide. Levees are not always present, and the external margins of the loops are uneven. The traces bear some similarities to *Psammichnites*, but transverse or arcuate internal structures and a distinct medial dorsal structure is not observed in the present materials.

**Interpretation:** *Psammichnites* has been interpreted as traces of gastropods or other subsurface vagile animals with siphons (Mángano et al., 2002).

**Remarks:** *Psammichnites* is known from full marine settings, ranging from Cambrian to Carboniferous (Mángano et al., 2002).

*Treptichnus* isp.  
(Fig. 4D)

**Locality:** DGA16-373.

**Description (5 specimens):** Simple or zigzag cylindrical burrows, straight or gently curved, thinly lined, smooth, horizontal to sub-horizontal, stacked upon another in vertical plane. The thickness of the burrows is around 1 mm.

**Interpretation:** *Treptichnus* is interpreted as feeding traces made by vermiform animals (Buatois et al., 1998), and some ichno-species are possibly made by priapulids (Vannier et al., 2010).

**Remarks:** *Treptichnus* has been recorded from a wide range of environments, including lacustrine, brackish tidal flat, shallow marine and deep marine environments (Buatois and Mángano, 1993; Uchman et al., 1998). The stratigraphic range is Vendian/Early Cambrian to Eocene (Buatois and Mángano, 1993; Uchman et al., 2005; Hammersburg et al., 2018).

## 5. Ichnofacies and depositional environment

The concept of ichnofacies was introduced by Seilacher (1964) as a classification to distinguish between trace-fossil assemblages that characterize different continental and marine depositional environments. Since then, there has been a growing number of studies on the relationships between ichnological facies and sedimentary environments, including detailed works on trace fossils and ichnofacies in deep-water environments. However, along with the accumulating documentation from ancient deep-water settings, there are also cautionary notes, pointing out that due to the lack of empirical data from recent deep-water environments, some of the published studies and approaches are misleading (Shanmugam, 2018).

The trace fossils recovered from the Fjellvollen Formation can be grouped into the *Nereites* ichnofacies, which generally is characterized by graphoglyptids and meandering trace fossils (Seilacher, 1967, 1974). Initially, the *Nereites* ichnofacies was described as typical for turbidite-dominated, flysch deposits in deep-marine basins (trenches) in the front of evolving orogens (Uchman and Wetzel, 2012). Uchman (2004) suggested that colonization of the deep-sea by graphoglyptid-producers in the Ordovician initiated the development of the archetypal *Nereites* ichnofacies. The Fjellvollen Formation consists of predominantly siliciclastic deposits, with distal turbidites, including thin-bedded siltstone and shale with minor sandstone beds in its lower 200–500 m (Gasser et al., 2022). In this respect, the recovery of *Nereites* ichnofacies within the formation concurs with the original ichnofacies model.

The lack of recoveries of in-situ body fossils in the Fjellvollen Formation is in contrast to the prolific fauna documented in the adjacent and time-equivalent Hølanda Group, from which fossil brachiopods, echinoderms, gastropods, trilobites, conodonts and graptolites have been recorded (Getz, 1890; Strand, 1948; Blake, 1962; Berry, 1968; Bockelie, 1974; Neuman and Bruton, 1974, 1989; Yochelson, 1977; Bergström, 1979, 1997; Schmidt, 1984, 1987; Spjeldnæs, 1985; Neuman et al., 1997). As discussed below, the record of *Nereites* ichnofacies trace fossils in the Fjellvollen Formation indicates that the difference in faunal compositions between the Fjellvollen Formation and Hølanda Group can be related to the depositional settings, with the Fjellvollen Formation representing distal, deep-

water deposits, compared to more shallow marine deposits, with richer biodiversity in the Hølonnda Group. Some of the warm-water faunal assemblages of the Hølonnda Group (Hølonnda Platform) are of distinct North American affinity (Bergström, 1979; Neuman and Bruton, 1989; Maletz, 2011), providing evidence for the tectonic model with the Hølonnda Shelf located to the west of the Ilfjellet Basin (Fig. 8) as outlined by Gasser et al. (2022).

Fine-grained turbidite systems commonly contain some of the most spectacular ichnofaunas described from the fossil record with respect to diversity, abundance, and complexity (Buatois and Mángano, 2011 and references therein). The trace fossil assemblages recovered in the Fjellvollen Formation are medium diverse, with 15 ichnogenera/-species identified. Most of the recovered ichnotaxa represent post-depositional forms, such as *Dictyodora* isp., *Neireites* isp., *Palaeophycus* isp., and *Treptichnus* isp. A generalized depositional model of the Fjellvollen Formation in the Ilfjellet rift basin, with fan-fringe and adjacent basin plain settings, and some of the trace fossils recovered in the *Nereites* ichnofacies is shown in Fig. 8.

In the Fjellvollen Formation there are no dominant taxa of trace fossils, but most common forms are simple looping ridges of *Gordia* and meandering traces of *Helminthoidichnites tenuis* and *Dictyodora*. In deep-sea facies *Dictyodora* is known from the Ordovician to the Permian, and Uchman

(2004) suggested that this ichnogenus could be used with some caution in stratigraphy. Here, *Dictyodora* cf. *tenuis* sensu Uchman et al. (2005) recorded from the Fjellvollen Formation closely resembles the specimens reported from the inferably Middle Ordovician Vuddudalen Group farther north in the Trondheim Nappe Complex.

Even though the *Nereites* ichnofacies is most often associated with deep basins, it is known to occur over a wide bathymetric range (Uchman and Wetzel, 2012). In the Early Cretaceous Kamchia Formation in Bulgaria, Uchman and Tchoumatchenco (2003) found a mixture of forms typical of both the *Nereites* ichnofacies (*Squamodictyon*) and the *Cruziana* ichnofacies (*Curvolithus*, *Gyrochorte*). They suggested that the Kamchia Formation was probably deposited in an offshore to deeper setting with storm sand layers and marly background sedimentation, and that storm-induced currents transported producers of *Cruziana* ichnofacies traces from the shelf into the deeper sea (Uchman and Tchoumatchenco, 2003). In the present material we find ?*Curvolithus* together with *Dictyodora*, *Gordia*, *Helminthoidichnites* *Monomorphichnus* and *Protovirgularia*. Lockley et al. (1987) introduced the *Curvolithus* ichnofacies as a subset of the *Cruziana* ichnofacies, typically found in settings with high sedimentation rates. MacEachern et al. (2012), however, describe the *Cruziana* ichnofacies as typical of relatively low-energy, semicohesive muddy substrate with variable

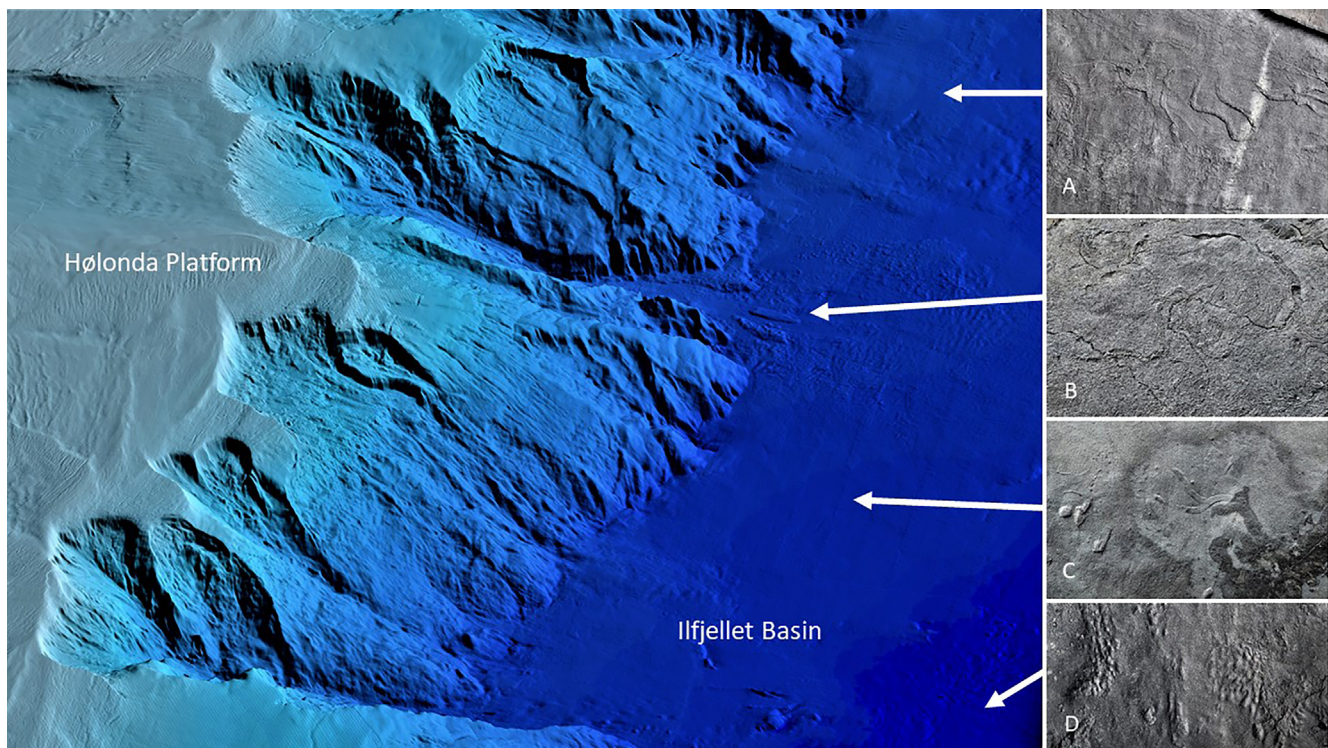


Fig. 8. Generalized depositional model of the Fjellvollen Formation, with fan-fringe and adjacent basin plain settings, and some of the trace fossils recovered in the *Nereites* ichnofacies in the Ilfjellet rift basin. (A) *Helminthoidichnites* a grazing trace (pascichnion), most likely produced by vermiform animals. (B) *Dictyodora* typically found in deep water turbidity flow deposits. (C) ?*Phycodes* and *Gordia* found in association with small-scale contourites in the Fjellvollen Formation. (D) *Nereites* isp., typically found in deep water pelagic muds on abyssal plains.

sedimentation and erosion rates. In the metasedimentary succession in the Trondheim Nappe Complex, *Curvolithus* is found in various lithologies from sandstone-dominated sequences to monotonous units of shales/slates, suggesting that this ichnogenus was generated in eurybathic environments (Smelror, personal observations).

In his cautionary note, Shanmugam (2018) points out that physics and hydrodynamics of deep-water sedimentary processes are difficult to observe and that physical processes responsible for transporting sediment downslope into the deep sea still are poorly understood. However, large amounts of new observations and measurements from various deep marine settings have been accumulated through national and international programs in recent years, including high-resolution data from various deep-water settings like contourites and turbidites (Bøe et al., 2015, 2020; Thorsnes et al., 2020). In the Fjellvollen Formation bottom current deposits are observed at several localities. In the present material, the trace fossils *Gordia* isp. and *Phycodes* isp. are recorded within turbidites at locality TGR16-353 (Fig. 7B). Both these trace fossils are undiagnostic with respect to ichnofacies, as they are known from various lacustrine to deep-water marine environments.

The abundance of meandering and looping trace fossils in the Fjellvollen Formation is comparable to what is found in the inferably time-equivalent Vuddudalen Group farther north in the Trondheim Nappe Complex, where trace fossils of the *Nereites* ichnofacies also have been found (Uchman et al., 2005). Both successions comprise mainly distal turbidites and deep marine deposits. The main difference is that while *Megagraption* isp. and *?Paleodictyon* are most typical features of the assemblages found in the Vuddudalen Group (Uchman et al., 2005). These two taxa have not been recorded in the Fjellvollen Formation. Graphoglyptids like *Megagraption* appear to have been well adapted to stable oligotrophic conditions and are typical indicators of a K-selected stratigraphy, indicating stable environments (Uchman, 2004). The typical *Nereites* ichnofacies with common graphoglyptids is found in very low-energy silty to muddy marine environments characterized by extremely slow deposition (MacEachern et al., 2012). The lack of records of *Megagraption* in the Fjellvollen Formation may be related to active tectonic processes and more unstable and varied depositional conditions, resulting in possibly higher sedimentation rates in the extensional Ilfjellet Basin during deposition of the Fjellvollen Formation.

## 6. Conclusions

The Ordovician Fjellvollen Formation (~475–463 Ma) is a part of the complex volcano-sedimentary Ilfjellet Group that formed in a rift basin along the Laurentian margin (Gasser et al., 2022). The formation has a maximum preserved thickness of around 2.3 km and consists predominantly of siliciclastic deposits, with mainly distal

turbidites, including thin-bedded siltstone and shale, and minor sandstone beds in its lower 200–500 m (Gasser et al., 2022).

Depositional conditions and assemblages of trace fossils recovered in the Fjellvollen Formation is typical of the *Nereites* ichnofacies, which is generally found in distal turbidites and deep marine basinal deposits. The trace fossil assemblages are medium diverse, with 15 ichnogenera/species identified. Most of the recovered ichnotaxa represent post-depositional forms, including *Dictyodora* isp., *Neireites* isp. and *Palaeophycus* isp. Additional recovered ichnotaxa include *?Alcyonidiopsis*, *Gordia*, *Helminthoidichnites*, *Monomorphichnus*, *Oikobesalon*, *Protovirgularia* and *Treptichnus*. In the Fjellvollen Formation there are no dominant trace fossil species, but the most common forms are simple looping ridges of *Gordia* and meandering traces of *Helminthoidichnites tenuis* and *Dictyodora*. Even though many of the taxa found in the Fjellvollen Formation are known from various types of depositional environments, several of the key traces indicate that they most likely originated in deep-water settings concurrent with the *Nereites* ichnofacies model.

No body-fossils have been reported from the Fjellvollen Formation, but the trace fossils indicate the presence of epi- and infaunas of various invertebrates. The lack of body fossils can probably be related to the *Nereites* ichnofacies depositional settings, with the Fjellvollen Formation representing distal, deep-water deposits, compared to more shallow marine deposits with richer faunas and higher biodiversity in the adjacent Hølonða Group. The abundance of meandering and looping trace fossils in the Fjellvollen Formation is comparable to what is found in the inferably time-equivalent Vuddudalen Group farther north in the Central Norwegian Caledonides, where trace fossils also have been assigned to the *Nereites* ichnofacies (Uchman et al., 2005). Both successions comprise mainly distal turbidites and deep marine deposits. However, the lack of graphoglyptids like *Megagraption* in the Fjellvollen Formation may indicate somewhat more proximal, unstable basinal depositional settings in the Ilfjellet rift basin.

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