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TRACE FOSSILS FROM THE UPPER DEVONIAN NEHDEN SILTSTONE OF WUPPERTAL-BARMEN (NORDRHEIN-WESTFALEN, GERMANY)

BY

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With Plates 37—39 and 6 Figures in the text

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Abstract

Tracks and trails from the Upper Devonian Nehden Siltstones of Wuppertal-Barmen, Nordrhein-Westfalen are described and interpreted. The siltstone beds show the full BOUMA-sequence, convolution, and reaction to dessication of the former muds below. Flute marks, obstacle scours, longitudinal furrows and ridges, groove marks, and knobby scour moulds are often transected by tracks and trails. Impressions of fossil tests are present. Load structures are common only in few layers. The trails now preserved on the bottoms of the siltstones were formed in each case on the surface during the interval between phases of current erosion and final burial of the mud surface. Grazing, crawling, resting and burrowing activities of a variety of benthonic animals are evident. Two new species are described, of *Cruziana* and *Belorhaphe* respectively. The trace-fossil fauna is not flysch-like as previous authors suggested. Owing to low oxygen supply in the bottom water burrowing was absent from the muddy sediments before erosive current action occurred.

Key words:
Trace Fossils, Upper Devonian, Flysch-Problem.

Zusammenfassung

Die Lebensspuren der oberdevonischen Plattensandsteine von Wuppertal-Barmen, Nordrhein-Westfalen, werden beschrieben und gedeutet. Die einzelnen Siltsteinlagen weisen die volle BOUMA-Abfolge, interne Verfaltung und Reaktion auf Austrocknungserscheinungen der darunterliegenden Schlamme auf. Strömungsmarken, Auskolkungen, Kritzungen durch driftende Körper, Längsfurchen, Längsrücken und knotige Ausspülungen werden oft von biogenen Spuren durchschnitten. Abdrücke der Hartteile fossiler Tiere haben sich erhalten. Knollige Strukturen, die bei Gewichtsausgleich entstanden, sind nur in wenigen Lagen ausgebildet. Die heute an der Basis der Siltsteinplatten erhaltenen Spuren wurden immer auf der Oberfläche des schlammigen Meeresbodens angelegt, und zwar in einem Zeitraum zwischen Strömungserosion und Verschüttung der Sedimentoberfläche während der Ablagerung der Siltsteinlagen. Eine Anzahl verschiedenartiger, benthonischer Tiere hinterließ Spuren weidender, kriechender, ruhender und grabender Tätigkeit. Zwei neue Arten der Gattung *Belorhaphe* und *Cruziana* werden beschrieben. Die Spuren-Fauna hat nicht die für Flysch typische Ausbildung, wie ander Autoren vorschlugen. Auf Grund niedriger Sauerstoffzufuhr der bodennahen Wasserschichten gab es keine grabenden Tiere auf und im schlammigen Sediment, bevor nicht abtragende, sauerstoffreiche Strömung einsetzten.

Schlüsselworte:
Spurenfossilien, Oberdevon, Flyschproblem.

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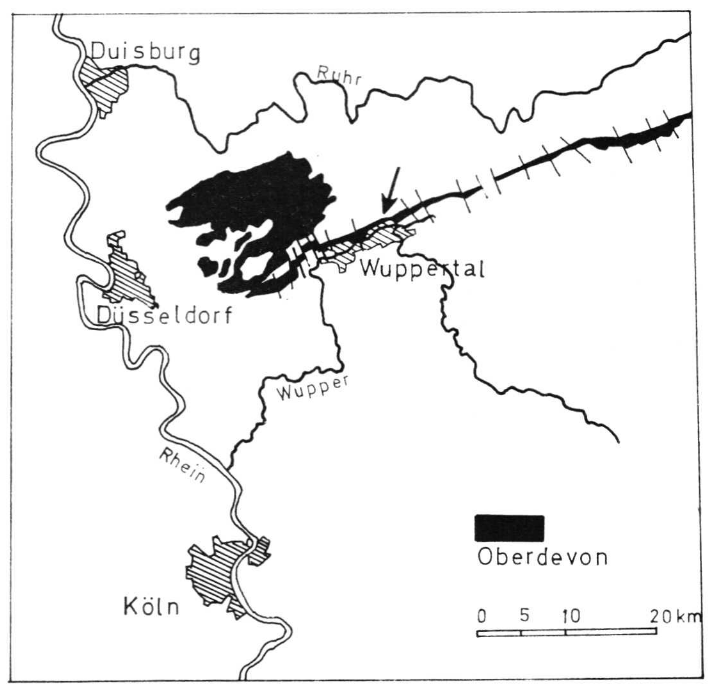
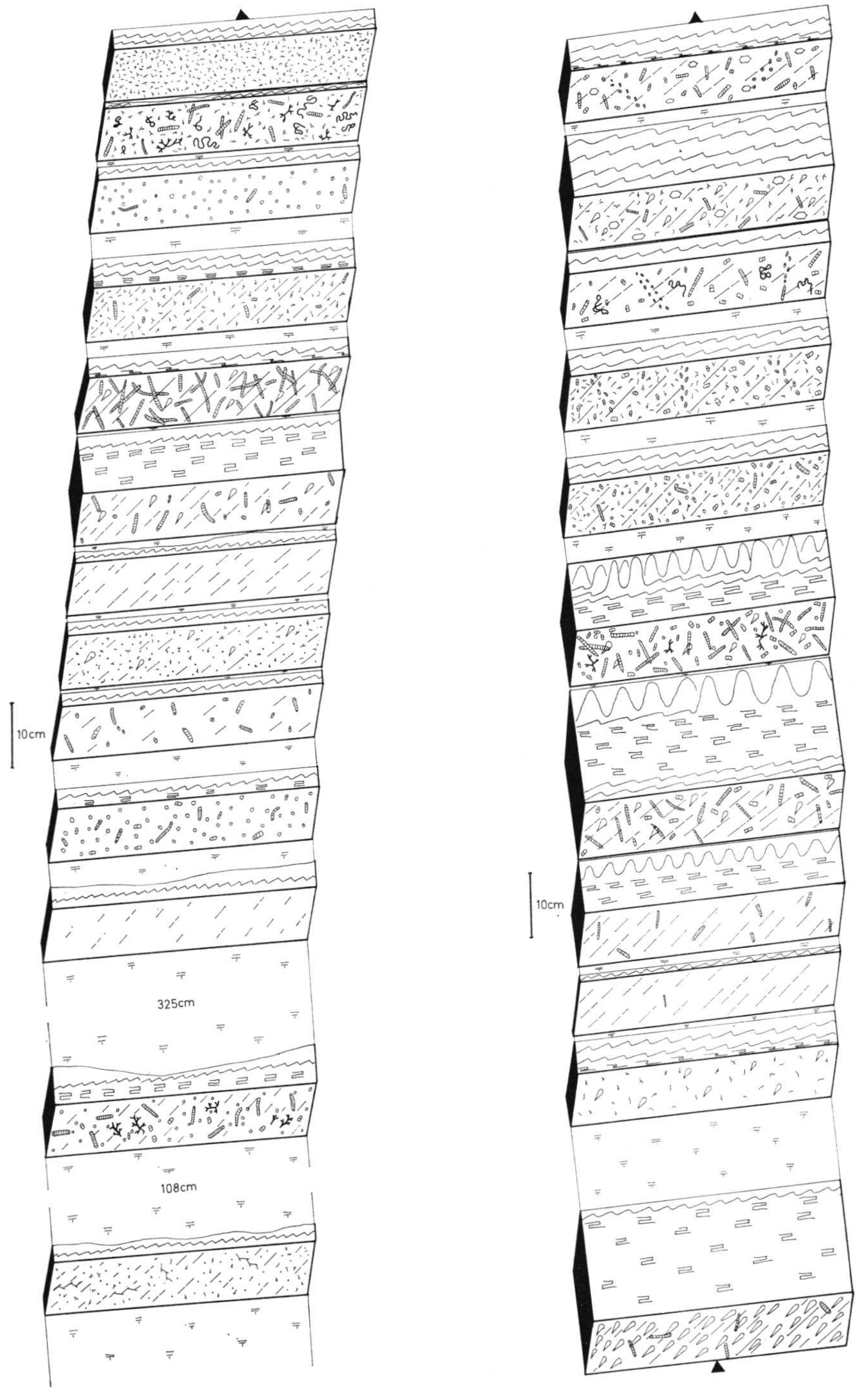
Introduction

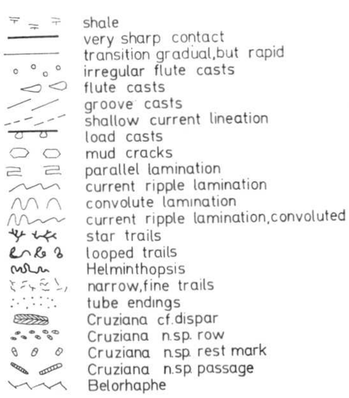
This paper is concerned with a trace fossil assemblage from the Upper Devonian Nehden siltstones at two localities in Wuppertal-Barmen, Nordrhein-Westfalen (Topographic map 1 : 25 000, No. 2721; Barmen). One outcrop is an old quarry in the "Beule" at Barmen (r. 85780; h. 84640), the other a small quarry at the bus terminal in the "Silberkuhle", Barmen (r. 86710; h. 85300). At the latter locality, the siltstone beds were measured and typical portions of this section are reproduced in Textfig. 2. The Nehden siltstone belongs to the Nehden formation of the lower Famennian. The lower Cypridinen-Schiefer grades into the Nehden siltstone called "Plattenstein" by Paeckelmann & Fuchs (1928).

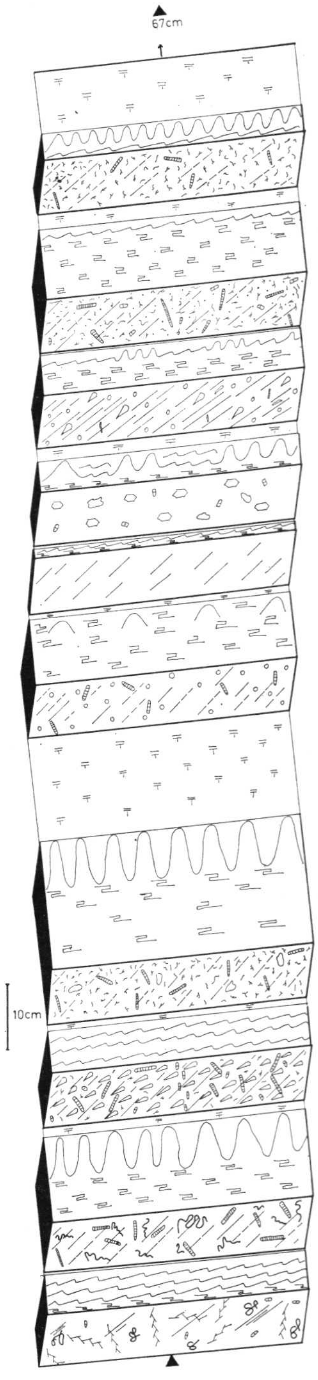


Textfig. 1. Map showing the general location of the localities in Wuppertal-Barmen (arrow).



Textfig. 2. The lower part of the Nehden siltstone sequence at the "Silberkuhle" at Barmen. The figure is drawn like a stair-case from below. One can see the soles of the silt beds with marks and trails, as well as the vertical section through the silt bed and the shale between silt beds. The vertical part of a stair in this figure corresponds to the silt sole, the horizontal part of a stair to siltstone and shale section.

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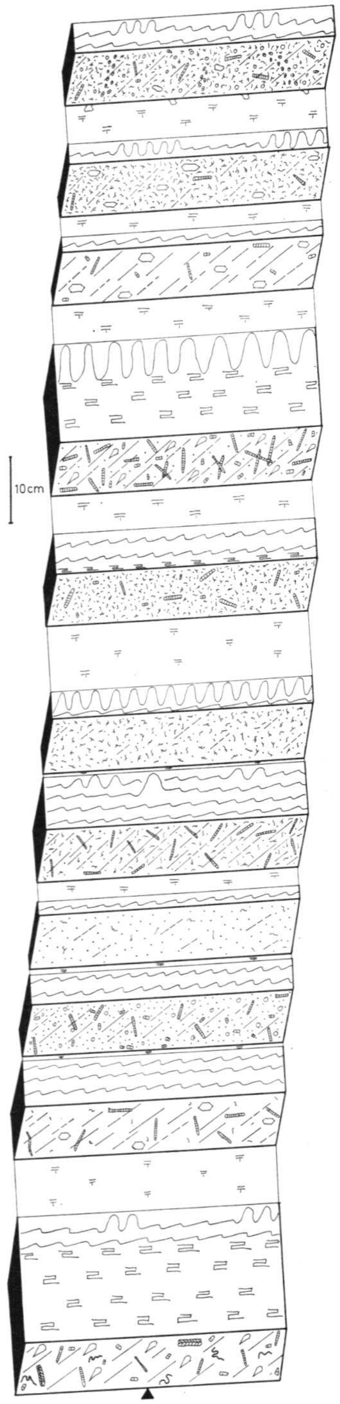
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The age of the lower Cypridinen-Schiefer is determined by the occurrence of *Cheiloceras*. In the upper part of the lower Cypridinen-Schiefer, 25 cm below the first siltstone bed, limestone lumps have been found. They were dissolved in monochlor-acitic acid and yielded the following conodont fauna (identifications by Dr. H. P. Schönlaub, Wien):

Palmatolepis rhomboides Sannemann
Palmatolepis glabra glabra Ulrich & Bassler
Palmatolepis minuta minuta Bransom & Mehl
Palmatolepis gracilis gracilis Mehl & Ziegler
Palmatolepis tenuipunctata Sannemann
Palmatolepis glabra pectinata Ziegler

This fauna belongs to the *Cheiloceras* zone, to IIß, and here in the *rhomboidea* zone.

The trace fossils so commonly seen on the well exposed soles of the Nehden siltstones in the two outcrops began to interest the present author when discrepancies with the ideas of previous workers showed up (Paeckelmann & Fuchs, 1928; Schindewolf, 1926; Kühn-Velten, 1955, 1968; Plessmann, 1962 and Einsele, 1963 a and b). Trace fossils have never been described in detail from the siltstone. Only Rabien (1956) gives descriptions of trace fossils, which he found in the Upper Devonian sandstones from the Waldeck Syncline, but does not illustrate them.

Sedimentary environment

Consistency of the silt beds

The Nehden siltstone sequence consists of graywackes alternating with shale. The grain size of the particles never exceeds 100—120 microns (Bouma, 1962 and Einsele, 1963). The sand fraction with grain size of more than 0,062 mm never reaches 50 % of the whole; the beds are therefore to be called sandy-muddy siltstone or clay-sand siltstone. Bouma (1962) says that there is indistinct grading and Einsele (1963) shows that grading in the Barmen section is good, measured in Wuppertal on a 10 cm thick bed.

Einsele stated that often there is a sharp boundary between a given siltstone and fine-grained shale at the top of the layer. This is found to be true in the measured section and in the "Beule" quarry.

Thanks to Dr. Beckmann, Bonn, an X-ray diagram of the clay minerals from limestone lumps, 25 cm below the first silt bed (at the trolley-bus terminal) could be made, showing that more kaolinite than illite is present. Chlorite is a prominent trace mineral. With caution, deposition close to the shore can be deduced from this assemblage. This agrees with the picture given by Plessmann (1962), who believes that the material of the Nehden siltstone sequence is derived from the shelf of the North Continent (Old Red Continent).

Lamination and cross stratification

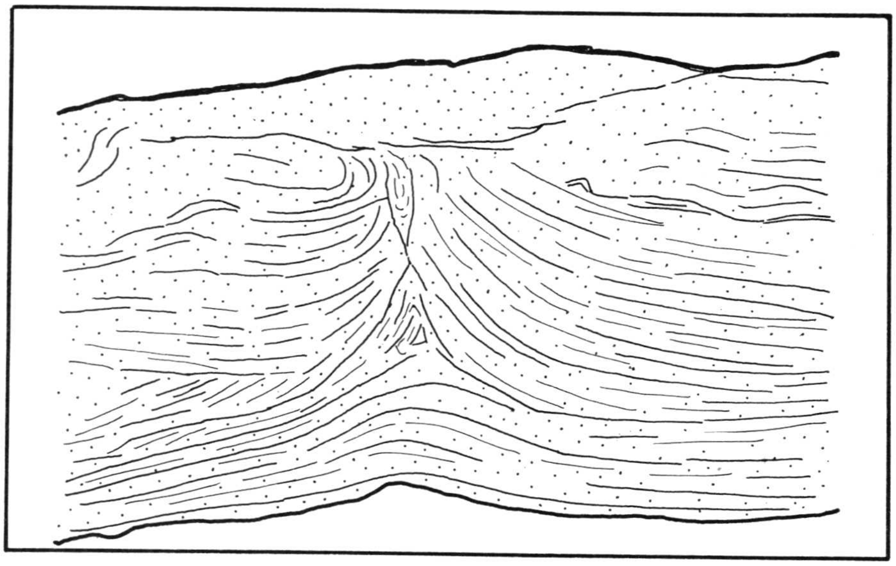
Bouma (1962) wrote that parallel lamination and current ripple lamination are predominant structures in the Nehden siltstones. The full Bouma sequence Ta-Te (Lower interval of parallel lamination = Ta, followed by an interval of current ripple lamination = Tb, an upper interval of parallel lamination = Td, and closed by a pelitic interval = Te) is present and can be observed in few beds. Mostly only parts of the sequence are preserved in the silt beds. Bouma (1962) only found the sequene Tb—Te, which is in fact the most common type, besides simple cross-bedded layers. Current cross stratification was used by Einsele (1963b), along with other current marks, to reconstruct the direction of flow (W—E).

Convolute lamination

Convolute lamination is a very common feature in the Nehden siltstone of Barmen. RABIEN (1956), PLESSMANN (1962), and particularly EINSELE (1963a) described convolute lamination from these or similar outcrops in the Nehden siltstones. Intensity of convolution depends on the thickness of the layer, as was observed by KÜHN—VELTEN (1955). Convolution occurs in beds from 2—30 cm thickness (EINSELE, 1963a). EINSELE has found convolute lamination only in silt beds that were definitely cross-bedded. This is not correct. Though most of the convolute lamination occurs in cross-bedded layers, horizontally laminated layers are convoluted as well (Textfig. 2). Convolute lamination in three dimensions shows a pattern of crests and troughs. In cross-section, convolute lamination ranges from gentle corrugations to highly contorted and folded patterns. The deformed zone may include all but the lowermost few millimeters of a siltstone, but never extends into the overlying shale. Contrary to the opinion of EINSELE (1963a), the underlying shale in some cases is also involved in the convolution and is injected into the middle of the fold (observed in a 7 cm thick bed in the "Beule" quarry). In the measured profiles there are beds with narrow convolution and others with only shallow and widely distributed convolutions. Sometimes the intensity of convolution changes within one bed.

Many authors have developed ideas and models for the formation of convolute lamination. But the most probable origin of these structures is that described by EINSELE (1963a) of the Nehden siltstones from the fossil record and by WUNDERLICH (1967) from the intertidal flats of the North Sea. He found convolute lamination in quickly deposited cross- or laminar-stratified beds in the Watten area. In the intertidal flats of the Verdrunken Land of Saeftingen, near Antwerpen, I was able to study this type of sediment myself. Here the fill of an old channel developed convolute lamination in a moment when a shock was applied. A footstep was sufficient to trigger convolution, but it had also been triggered merely by sedimentary action. The rippled surface of the fine, sandy sediment assumed a soupy appearance and the formerly solid-looking surface started to flow like a mud suspension, the ripple crests sinking and water appearing on the sediment top. The tops of convolute folds sometimes opened and black sediment from the shallow-lying, reducing environment was spilled onto the surface. After some minutes, the sediment stabilized again. The formerly rippled surface now was a shallowly pitted surface, with irregular, shallow depressions and mounds very similar to the upper surface of the Nehden siltstones.

Convolute lamination is of great importance for the interpretation of the deposition of the Nehden siltstones, because it gives us a notion of the rate of sedimentation. Convolute lamination is caused when a swiftly deposited, fine-grained, muddy sediment reacts as a hydroplastic body. So the rate of sedimentation in convoluted beds must have been high. A structure, which must have developed from a convolute fold that opened and spilled silt onto the surface in a Nehden Siltstone bed is shown in Textfig. 3.



Textfig. 3. Section through a siltstone bed. A convolution fold that opened to the surface. The unstratified siltlayer was extruded onto the surface. Length 5 cm, height 3.5 cm; drawn from a photograph.

Current marks

Currents produced various types of markings on the shale surface below the siltstone soles by turbulent scour and dragging objects over the bottom.

a) Flute marks

(Pl. 37, Fig. 4; Pl. 38, Fig. 1; Pl. 39, Fig. 9)

Flute casts are elongate bulges on the soles formed, where depressions, scoured in the underlying substratum by current action were subsequently filled with sand. The proximal part of the bulge of a flute cast, lying upstream from the point of highest elavation, slopes downward much more steeply than the distal portion of the flute. The flute casts on a particular sole of the Nehden siltstone have about the same shape. The most common ones are of the asymmetrical, flat type (Pl. 37, fig. 4); in some beds, simple conical types occur together with the corkscrew type, having a spiral welt on the narrow upstream end (Pl. 38, Fig. 1).

Flute marks will continue to grow only if the current velocity is maintained above a certain limit of relatively large velocity. Many authors have recorded flute marks from the Nehden siltstones. PLESSMANN (1962) believed that the Nehden flute marks were generated by a strong water or suspension current immediately before the final filling of the flute. EINSELE (1963b) measured the direction of the flutes in the Nehden siltstones at Barmen and with groove marks and cross-bedding directions reconstructed the direction of sediment movement (W to E). PLESSMANN's idea of filling right after formation cannot be correct, because surface trails of benthonic animals cut across flutes sharply and are without doubt made after the formation of these flute marks (Pl. 37, Fig. 4; Pl. 38, Fig. 1; Pl. 39, Fig. 9). The trails never show any kind of relationship to the current direction and are distributed randomly, indicating that the flutes were open and not immediately filled after current action had ceased. Before burial of the flutes by the silt bed, a period of quiet water condition prevailed. The trails go up and down the walls and the bottom of flutes without being disrupted (Pl. 37, Fig. 4). They are not made within the sediment, but on the sediment surface because in sawed sections of flute casts a disturbance of the fine laminations has never been found.

b) Obstacle scours

(Pl. 37, Fig. 5)

Common are longitudinal obstacle scour moulds washed out behind small obstructions and traces. Traces seem to be the most common obstructions, but in one case a goniatite test served as an obstacle giving rise to a "Hufeisenwulst", i. e. a crescent mark (Pl. 37, Fig. 5). These obstacle scours, like the flute casts, may show interruptions by trails, similar to those described for the flute marks.

c) Longitudinal furrows and ridges

(Pl. 38, Fig. 5; Pl. 39, Fig. 5)

Very shallow current lineation in the form of longitudinal furrows and ridges occurs on most soles. Where obstructions were present this shallow current lineation grades into obstacle scours and flute marks (Pl. 39, Fig. 1). The lineation may be casts of very shallow fluting and grooves modified by fluting. Often current lineation is the original surface pattern on which benthonic animals made a profusion of trails. Here again, current came first, then calm water with activity of benthonic animals and finally preservation by deposition of the silt. Sometimes the trails are faded out again by currents and current lamination is the last produced surface feature.

d) Groove marks

(Pl. 37, Figs. 5, 6, 7, 9; Pl. 38, Fig. 5; Pl. 39, Figs. 1, 5, 7)

Groove marks are linear and usually straight ridges on a sole. They vary in width from 1 mm or less up to 5 cm across and usually are quite shallow. The grooves have clean cut sides and sometimes ridges on the bottom parallel to the direction of the groove (Pl. 37 Fig. 9). Groove moulds are irregularly spaced over a bedding plane and occur in different density on different soles (Fig. 2). They are the most common mark in the profiles and can be found on almost every sole. Intersecting sets are common, but they never deviate more than 30 degrees from the principal direction. Bodies of benthonic animals, mud pebbles, or plant fragments may have been the agents incising the groove marks. PLESSMANN (1962) and EINSELE (1963b) measured the direction of groove marks and came to the same conclusion: that the direction of sediment transportation in Barmen was from W to E or SW to NE.

PLESSMANN (1962) observed the difference in direction of the groove marks and interpreted it as directional change of a suspension current in its flow before settling down. This probably is not the case. It is believed that different directions of groove marks are made by different currents. Groove marks are just like all the other current marks described so far intersected by trails of benthonic animals. Sometimes a trail intersects a groove mark of one direction and itself is intersected by another groove mark of another direction. This has been observed several times.

One wide groove mark was intersected by a winding trail coming from the adjacent sediment surface and going down the walls curving on the sole and going up on the other side.

e) Prod marks

(Pl. 37, Figs. 5, 7; Pl. 39, Fig. 1)

Prod marks are elongate depressions impressed most deeply downstream. Sometimes groove marks end similarly. The prod marks are mostly only a few millimeters long and rather common (Pl. 39, Fig. 1). A tool hit the sediment surface at a high angle and was halted and lifted into the current again. A specific type of prod mark resembles very much the one figured by SEILACHER & HEMLEBEN (1966, Fig. 10). Here from a ridge curving parallel branches turn off at a low angle on one side. Possibly this was imprinted by a trilobite carapace when bounced on the sediment surface. Another prod mark (Pl. 37, Fig. 7) was made by a round, hollow tool forming a ring groove.

f) Knobby scour moulds

(Pl. 37, Fig. 3)

Many soles are covered with an irregular scaly pattern of non-orientated structures. Smooth soles with prod and groove casts often grade into an irregularly pitted surface. Here again trails are either destroyed by knobby scour moulds or are formed on them.

g) Wrinkled surface

Pl. 37 Fig. 6 shows the surface of a sole with wrinkles. SEILACHER (1960b) described similar features from the lower Devonian Hunsrück shale. He interprets their origin by tangential pressure due to the current causing wrinkles on the plastic mud surface. The wrinkles were made before the trails had been formed as can be seen in Pl. 37, Fig. 6. Here a *Belorhaphe* trail crosses wrinkles without showing any deformation, so that SEILACHER's explanation regarding their origin can be accepted for the Nehden siltstone, too. Wrinkled surfaces were also figured by SCHINDEWOLF (1926, Fig. 2).

Impressions of animal tests on the silt soles

Goniatite, lamellibranch, and trilobite casts on the silt soles are not uncommon. The original shell has been washed away leaving the cast (Pl. 37, figs. 2, 3, 5) which was later filled by silt. One goniatite served as an obstacle before being washed away (Pl. 37, Fig. 5). Only in one case the original shell was still preserved and not washed away and that was a *Posidonia* shell figured in Pl. 37, Fig. 1. The washed-off shells, when bounced on the sediment surface, may have produced prod marks, similar to the prod marks figured in Pl. 37, Fig. 7.

Wood fragments and clay balls

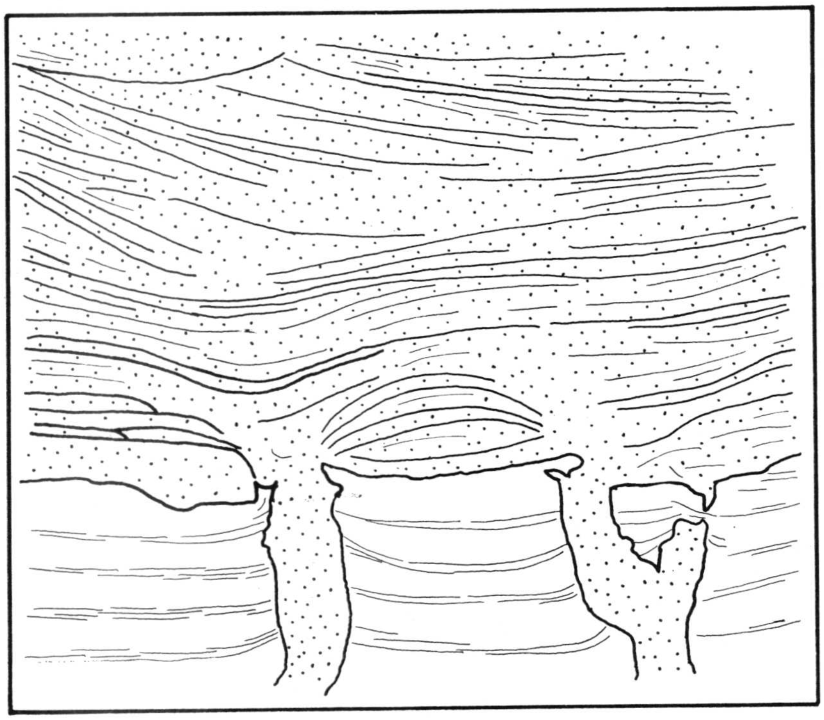
From thick beds of the Nehden siltstones PLESSMANN (1962) mentioned clay balls and drift wood fragments. Rarely layers of these are developed in the upper part of the measured section, but in the quarry at the "Beule" they are commonly found associated with thick beds. Plant remains have also been found in the shales, a feature EINSELE (1963a) also observed. Mud pebbles can be formed in great depth as well as in shallow water, if current conditions are the same.

Load and injection structures

Load casts have been observed at this locality by BOUMA (1962). In some layers they are common but never very strongly developed and always on the silt sole. Load marks cut across all kinds of organic and inorganic marks on the soles and also disturb all internal stratification. Injections of the underlying shale into the mixed-up structures are common. Burrows were never made after formation of these projections of silt and fine sand into the mud surface.

Shrinkage cracks

SCHINDEWOLF (1926) mentioned dessication cracks on the siltstone soles of the Nehden siltstones in Barmen. He interpreted them as fissures that were formed in air-exposed muds in an intertidal environment. PLESSMANN (1962) was not able to find similar forms and agreed with RABIEN (1956) that these structures most probably were non-existent. The observations of SCHINDEWOLF are without doubt correct and it was possible to find structures similar to dessication cracks on the soles of many different layers of the Nehden siltstones (Fig. 2). A closer examination of the cracks, however, showed that RABIEN's and PLESSMANN's doubts with respect to SCHINDEWOLF's interpretation as aeresis cracks were justified.



Textfig. 4. Section through a siltstone bed. Fissures in the shale filled with material are like the siltstones above in composition. The laminae at the base of the siltbed are disrupted and sagging is visible in the layers further above. Thickness 2.5 cm; drawn from a photograph.

D e s c r i p t i o n : The fissures are up to two centimeters wide and irregularly dispersed on the soles, often forming polygonal patterns. Usually the width of cracks is only a few millimeters. Depending on their width they extend up to three centimeters into the shale more or less parallel walled or becoming more narrow in depth. They cut sharply through marks and trails on the siltstone sole. The fissures in the shale are filled with material exactly like the above siltstones in composition. Sectioned siltstones show sagging or disruption of laminar or cross-bedding structures above the fissures (Fig. 4). Sagging is easily visible in the laminations at the base of the siltstone bed and decreases further up. At the base, the stratification is disrupted, then sagged and further up only somewhat bent down. Depending upon the thickness of the fissures, the sagging dies out within a few millimeters or centimeters above the fissures. In the measured section, the cracks occur in shales up to 6 cm in thickness. They were observed in 16 different siltstone layers in the profile.

Interpretation and discussion:

It can be concluded from the description that these structures must have been formed after sedimentation of the siltstone, because sagging is observable within them above the fissures. Trails and marks were filled by the silt, thus open fissures in the clay would have been filled as well. Therefore these former aercsis cracks (SCHINDEWOLF, 1926) are in reality syneresis cracks (WHITE, 1962). Syneresis is the expulsion of part of the liquid phase in a liquid-solid suspension, when internal forces of attraction are greater than internal forces of repulsion between the particles of the solid phase (WHITE, 1961). WHITE conducted experiments with flocculated clay-minerals and found fissures developed in the suspension under a water cover. The fissures began to develop in a beaker within 30 minutes to an hour after sedimentation and resembled known dessication cracks from the fossil record. WHITE figured Chester sandstones, which show imprints of cracks on the sole, very similar to the structures observed on the Nehden siltstone soles. He interpreted them as being deposited on thin mud beds containing syneresis cracks. The filling indicated that the cracks were present, when the sandstones were being deposited. Unfortunately, he does not mention sectioning trough the sandstones above the fissures, leaving some doubt as to whether the cracks opened before or after deposition of the sand. As for the Nehden siltstones, there is no doubt that the fissures opened after deposition of the silt. The silt was still quite mobile when cracks opened and were filled by the flow of the basal layers of the silt bed. The entire silt bed already had been laid down at the time of opening of the cracks, because shallow depressions in laminations above filled fissures can be found even in the upper part of a bed.

Shrinkage cracks in Tertiary clays formed under a sediment cover are described by RICHTER (1941) and called "fissures intrasedimentariae". However, these structures were not filled. In conclusion, the Nehden fissures can be called dessication cracks, formed under water and under sediment cover very early in diagenesis and caused by dehydration of the mud.

Fauna

Body fossils

In the lower Cypridinen-Schiefer, a quite well preserved fauna is abundant. Planktonic ostracodes completely cover some bedding planes. Among cephalopods *Bactrites* is the most common, followed by goniatites and orthocones nautiloids. Some layers are filled with tests of orthocone cephalopods which have random distribution on the surface of the clay beds and never show any preferred orientation. The same is true for the bivalves *Posidonia* and *Buchiola.* The former is more commonly present and is the largest body fossil found in the shales. Rarely brachiopods *(Lingula, Productella, Chonetes* and indet. brachiopods) are found. They are all of small size except some specimens of *Lingula.* Small gastropods and a few crinoid remains are present. Trilobites are very common. Many of them (about 50 %) are preserved in the so-called. SALTER-position (RICHTER, 1937). This position is indicative of sloughing of the blind trilobite *Phacops (Trimerocephalus) mastophthalamus.* The thorax with pygidium lies strechted out on the bedding plane, the cephalon is cut off and mostly lying in front of it upride down and directed with the posterior and to the thorax. The hypostome often lies in its original position in front of the thorax. RICHTER (1937) shows that this is the position typical for molting of this blind trilobite. This preservation reflects the biologic activity of this trilobite, and also the tranquil conditions, under which deposition took place and the absence of biological reworking of the sediment surface.

In shale layers, were limestone lumps occur (one only 25 cm below the first silt bed), the fauna is much riches and also benthonic animals, such as small single corals, colonial bryozoans and many small brachiopods are common. Here trilobite remains are very abundant, too, but never in the SALTER-position. Some of the limestone lumps are made up largely of crinoid ossicles. Also thin layers of crinoid limestone occur. Such layers are completely absent from the shales between the siltstones. RABIEN (1956) found no fossils at all in the shales between the siltstones of the Waldeck Syncline, which is in contrast to the measured sections at Barmen. Here the fauna typical for the lower Cypridinen-Schiefer is also found in the shales between the siltstones. In one thin band of shale, tests of 73 *Bactrites,* 15 othocone cephalopods, 51 goniatites, 1 trilobite (SALTER-position), very many ostracodes, 9 *Posidonia,* 4 *Bucholia,* 2 brachiopods, and 3 gastropods were found. Also *Chondrites* occur here — a difference to most fossil-bearing layers in the lower Cypridinen-Schiefer. Outside of this bed, which was studied in particular detail, trilobites, one crinoid with partly preserved cup and *Posidonia* shells were found. In some of the shale layers reworking has occurred. Here ostracods are concentrated in burrows.

In conclusion, it may be said that only a few of the body fossils preserved in the shale are benthonic. Brachiopods, gastropods and crinoids could also have lived as pseudoplankton on floating algae, such as *Sargassum* weed. RABIEN's (1956) conclusion from the fauna is that the Cypridinen-Schiefer was deposited below a depth of 200 m. This does not have to be the case, because a fauna similar to the one here described could be found in any kind of marine environment with restricted oxygen supply.

Trace fossils

Trace fossils are preserved within the sequence of the Nehden siltstones in three different ways:

1. As burrows in the shale: The mud-filled burrows are preserved in full relief.
2. On the siltstone soles: Originally these trace fossils were epireliefs (SEILACHER, 1964a) made on the mud surface or semireliefs made on the clay sand interface, later preserved by filling with silt from the silt beds and preserved as hyporeliefs on the siltstone soles. These surface impressions have always been concave originally, but are now always convex because of the silt pressed into the mud mould. Sometimes these moulds are separated by a thin shale layer from the siltstone soles and are then preserved in full relief.
3. On the upper siltstone surface: Here the original surface impressions are preserved and were made on the siltstone top and filled by muddy sediment.

The most common type of preservation is that with best preserved trace fossils on the siltstone soles.

Systematic descriptions

The following practice was adopted from HÄNTZSCHEL (1962), the trace fossil genera are described in alphabetical order.

Belorhaphe FUCHS 1895

Type species: *Cylindrites zickzack* HEER, 1877 (= *Belorhaphe* Auctt.).

Belorhaphe protopalaeodictyum n. sp.

Text-Fig. 6, Pl. 37, Fig. 6; Pl. 38, Fig. 2

Derivatio nominis: Initial form of *Paleodictyon* resembling *Belorhaphe*.
Holotypus: Specimen figured in G.P.I.Bo/Ba1 Bonn, No. 1. Paratypoid: Specimen figured in Pl. 37, Fig. 6, G.P.I.Bo/Ba2.
Stratum typicum: Nehden siltstones, Upper Devonian.

Definition: Sharply zig-zag shaped traces with short protrusions at the corners which connect the trail measuring 1—1,5 mm width and 10—15 mm in length from bend to bend and a similar smaller system of traces (0,5 mm wide) branching from the main track and forming an irregular hexagon network, with hexagons never completely closed.

Discussion: In general, only the wide zig-zag trails with short protrusions at the corners are preserved. In some cases, the connection of this trail with a system of small trails forming an imperfect *Paleodictyon* type network is present (Pl. 38, Fig. 2). The fine network is similar to structures described by NOWAK (1959) as *Protopaleodictyum* and KSIAZKIEWICZ (1958) as *Protopaleodictyon* (personal communication, VIALOV, 1968).

According to HÄNTZSCHEL (1962) these trails are *nomina nuda* because they were tentatively published with neither diagnosis nor named species. The name *Protopaleodictyon* was proposed for initial forms of *Paleodictyon* resembling *Belorhaphe*.

RABIEN (1956) described trails from the Dasberg sandstones from the Waldeck Syncline (Page 39), which could be identical with this trail, but the description is given without illustrations, so that some doubt remains.

One trail of *Belorhaphe* crosses a groove mark, disrupting it (Pl. 37, Fig. 6). This indicates that these trails must have been made on the sediment surface after the groove had been incised by current action. The trail was made before deposition of the silt on the muddy surface, because the grooves made by the animal are filled with undisturbed, finely laminated silt. There is no preference in direction, so that it is most probable that the trails were made in conditions of quiet water. The originator of the trail may have been a worm-like animal without test and of variable thickness depending on the specific action. SCHINDEWOLF (1926) figured a trail exactly like it (Fig. 2) and interpreted it as being formed on an intertidal flat.

Chondrites STERNBERG 1833

(Pl. 39, Fig. 8)

Very plant-like, regularly ramifying tunnel structures, which neither cross each other nor anastomose; width of tunnels remaining equal within a system. These burrows are preserved in some shales between the siltstones and in rare cases on the upper surface of the silt beds. Here a bundle of tunnels of a *Chondrites* system penetrates the upper surface of the siltstone forming holes about two millimeters wide. Besides the holes also the "twig system" is preserved along the clay-silt border in the upper part of silt beds. Here the branches are about one millimeter wide and the "twig" is four centimeters long. The holes made by the *Chondrites* tunnels in the silt terminate a few millimeters beneath the silt surface. The *Chondrites* system was built within the sediment after deposition. The animal building *Chondrites* never penetrated the siltstone and was only adapted to burrowing in mud. The burrows found in the shale are perfectly round and one millimeter wide. The shales are of different colours, layered dark grey to yellowish green. The *Chondrites* burrows are filled with material of the same colour as that of the succeeding strata, thus the change between the sediment filling the tunnel and the matrix is easely seen. There were never bundles of burrow uncovered by erosion and preserved on the silt soles, so it is probable that the burrows were formed deep in the sediment or only in the clay material directly above the silt beds.

The statement of RABIEN (1956) that no trace fossils are present in the Nehden shales of the Waldeck Syncline must be doubted, because in the very similar shales of Nehden siltstones at Barmen they are rather common and mostly *Chondrites*.

The *Chondrites* system has been reconstructed by SIMPSON (1956). He suggested a sipunculoid as the originator of this trace fossil. He stated that the occurrence of *Chondrites* in a sequence allows some deductions as to the conditions, under which accumulation took place. The bed with *Chondrites* is of marine origin and sedimentation was rapid, otherwise the tunnels would have collapsed, before being filled in. The water was calm, because in disturbed sediments the form of the *Chondrites* burrow deduced by SIMPSON could not have been constructed. SIMPSON thought that *Chondrites* was made by a single animal burrowing from one point. A relatively large animal with sac-like body and an extensible proboscis-like organ made the regularly branching, three-dimensional system. The flat "twig" developed on the silt surface was burrowed because the animal was able to select and exploit a special layer rich in food. FERGUSON (1965) belied that the filling of the burrows had occurred immediately after withdrawal of the proboscis from the portion of the burrow concerned. The surface tension between the much lining of the tube and the interstitial water of the surrounding sediment must have been sufficient to prevent the caving in of the walls, despite the vacuum created on withdrawal of the proboscis. If this had been the case, SIMPSON's deduction regarding the rate of sedimentation would be invalid, because the filling of the tubes was accomplished immediately by action of the animal and not by sedimentation.

Cruziana D'ORBIGNY 1842

Type species: *Cruziana furcata* D'ORBIGNY; [SEILACHER, 1955 (= *Bilobites* D'ORBIGNY)].

Cruziana barmensis n. sp,

Textfig. 5; Pl. 38, Figs. 1, 4, 5; Pl. 39, Figs. 2, 6, 9

Derivatio nominis: Locality of collection in Barmen.
Holotypus: Specimen figured in Pl. 37, Fig. 5, G.P.I.Bo/Ba3. Paratypoids: G.P.I.Bo/Ba4—6.
Stratum typicum: Nehden siltstones, Upper Devonian.

Definition: Shallow, pocket-like, rectangular pits, passages or shallow, horizontal burrows. Passages and burrows gently curving or straight, showing regularly spaced, transversal grooves, commonly bearing median ridge. Pits simple or aligned in an alternating series.

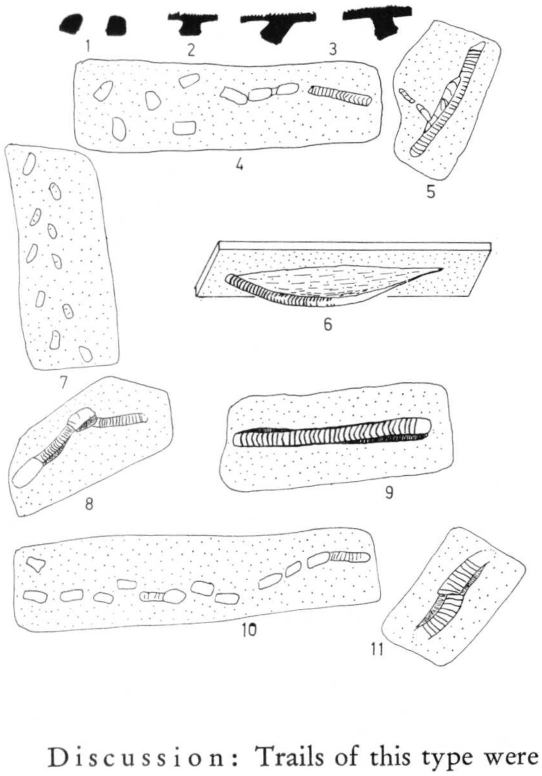
Description: The pocket-like pits are deepest in the center and become equally shallow at both ends (Textfig. 5, Fig. 4; Pl. 39, Fig. 7). They measure 1—8 mm in width and 2—15 mm in length. The shape is rectangular, with rounded edges, sometimes egg-shaped or similar to a coffee bean, but never with a prominent median ridge. The sole of the pit is flat and transverse grooves are rarely preserved. The angle between the sole and the side wall is about 90 degrees and the edges are sharp. The pits are mostly irregularly distributed on the sediment surface. They are preserved as casts on the siltstone soles and as original pits on many upper surfaces of the siltstones. In one case, a pit connected to a passage has been found in the parallel-laminated part within a siltstone bed.

In some cases, pits are combined in a series (Textfig. 5, Fig. 4, 7, 10; Pl. 38, Fig. 4). The alignment starts irregularly. Here the distance between pits is less than the length of the pit axis. The long axis being parallel to one another, within a short distance this changes into a regular alignment, in which the distance between pits is equal to the length of a pit. Here the pit axis are pointing away from an imaginary middle line at an angle of about 45 degrees (Textfig. 5, Fig. 7; Pl. 38, Fig. 4).

Occasionally a row of pits becomes a passage. In these regularly spaced transverse grooves are preserved (Textfig. 5; Pl. 38, Fig. 5). The distance between grooves is such that a series of 3—4 grooves corresponds to the width of the passage. The transverse grooves are thin and sharply imprinted. In the middle of the passage, a shallow ridge is sometimes preserved, then the transverse grooves are of crescentic shape (Pl. 38, Fig. 5). Mostly the sole of the trail is straight and then the transverse grooves are also straight. The corners between sole and walls are sharp and form about an angle of 90 degrees (Textfig. 5; Fig. 2). Most trails were burrowed to a depth equal to the width of the sole. If the trail has been burrowed deeper, the walls form an angle of about 135 degrees with the sole. The edges between sole and walls are still clearly cut. The transverse grooves continue across the edges between sole and sidewalls and terminate at the lower part of the sidewalls. Here longitudinal furrows are scratched into the wall.

The passages are mostly straight to slightly curved and never branching. At a crossing point the younger trail always cuts sharply across the older one burrowing deeper and destroying the other (Pl. 39, Fig. 6). In wide curves the sole of the trail is not horizontal to the sediment surface but inclined toward the inner side of the curve (Textfig. 5, Fig. 3). If the animal wanted to change direction in a sharp turn it had to scour a pit (Textfig. 5, Fig. 8; Pl. 38, Fig. 5). These pits are often found in the passages. They are broader than passages and also broader than resting tracks. Often these pits are of irregular shape depending upon the degree of directional change. The pits may reach a width of 2 cm, a length of 4 cm and a depth of 2 cm.

Often the trails dip shallowly below the shale surface and form full relief burrows. The sole and the walls are developed similarly as in the passages which opened to the sediment surface. In the burrows the ends of the transverse grooves at the base of the sidewalls and the two longitudinal furrows on the sidewalls can be observed especially well. The height of the burrows reaches 8 mm depending on the width of the sole. The burrows are up to ten centimeters long and lie parallel to and a few millimeters below the shale surface. Even in the straight burrows, the soles are often inclined. The pits observed in open passages are never developed in the burrows. The roof of the burrow forms either a high or shallow arch.



Textfig. 5. Different appearances of *Cruziana barmensis* trails:
1. Sections through burrows
2. Section through straight passage
3. Sections through bend passages
4. Resting tracks in connected to passage
5. Passage connected to an irregularly winding trail, made by some worm-like animal, giving an appearance of branching
6. Deeply dug-out passage
7. Series of resting tracks
8. Passage and scratch pits
9. Passage
10. Irregular alignment of resting tracks
11. Change in direction in a passage.

D i s c u s s i o n : Trails of this type were described and figured by PLESSMANN (1962; Fig. 1). In his material they were partly destroyed by current action. Also SCHINDEWOLF (1926; Fig. 3) figures this type of trail and interprets it as typical intratidal. RABIEN (1956) described the trace fossil fauna of the Nehden siltstones of the

Waldeck Syncline, but gave no figures. It seems as if his types number one and eigth are of the above described species. He observed that some passages had branches. This surely must be an error or his trail number one is a collective type combining different trace fossils. Number eight is an alignment of pits, probably just like the Barmen specimens.

Bilobate trails are described by SEILACHER (1960a). He demonstrated that a variety of organisms can produce pit and passage forms. SEILACHER figures (1960a, Tab. 1) *Bilobites* made by gastropods, phyllopods, and unknown animals. Here passages turn into pits and vice versa. In all cases, bilateral animals crawled on the ground burrowing shallowly. If they burrowed in place they made resting tracks reflecting the shape of the produces. If shallow burrowing and locomotion in the horizontal plain was made instantaneously, then pits in a series or plowed out passages are formed. This interpretation by SEILACHER is applicable to the trails here described.. The type of tracks and burrows made by the Nehden animal are foraging tracks *(Pascichnia),* burrows *(Fodinichnia),* and resting tracks *(Cubichnia)* (SEILACHER, 1964b). The passages record the animals search for food in the uppermost surface of the mud. The burrows were made when the animal dug in somewhat deeper, so that the sediment surface remained undisturbed above. The burrows were used only once.

The producer of the passages and pits was a bilaterally constructed animal with a hard test and feet or a crawling sole. This can clearly be seen in the transverse grooves on the sole of the passages, the furrows in the sidewalls cutting off the transverse grooves and in the shape of the trail. The animal was not able to make sharp turns, while continuing its way of foraging. If it had to, it accomplished it by stopping and making a scratch pit, so that the passages between pits are straight or gently curved. If a gentle curve was made, the sole slopes toward the inner part of the curve like in a race track. This way lateral bending of the test was not necessary and the turn achieved by dorsal bending. The carapace of a trilobite did not permit lateral bending (SEILACHER, 1959) so that a trilobite had to orient itself to the inside of the curve. This feature is strong evidence for formation of the Nehden trails by a trilobite or a similarly built animal. If a gastropod — also a bilaterally symmetrical animal with a hard test and a sole — had to make a curve in its course of foraging it had no difficulties in lateral bending, because the sole moves independently from the test. Recent and fossil gastropod trails therefore differ in this respect from the described trail (BANDEL, 1967).

Trilobites are commonly preserved in the shale between the siltstones. Some of these are found in a special orientation of the carapace and the cephalon described by RICHTER (1937) as "SALTER"-position. This is clear proof that trilobites lived in these muds that formed the shales and were not washed in or fell in from above. I believe that these trails were made by tribolites. The passages were made, while foraging through the sediment in the search for food or possibly eating sediment. The resting tracks were made when the animal burrowed shallowly into the sediment in a manner possibly similar to that of the Recent crustacean *Cragon* in the intertidal flats of the North Sea. In this example, only the antennae project above the sediment and search the water (SCHÄFER, 1962). The series were made, when the trilobite changed from one to the next resting place in a regular manner in regular turns. The trilobites lived on the sediment after the first current had formed the mud surface. They migrated up with the quickly deposited silt, alway staying on the surface and they populated the upper silt surface.

Cruziana cf. *dispar* LINNARSSON 1889

Pl. 37, Fig. 3

Description: The trail is 1—3 cm wide and up to 12 cm long. Passages and pits are preserved, both showing good transverse grooves that end in a middle ridge which is always prominant. The transverse grooves are narrow and at first form an acute angle with the median ridge and later curve until they are vertical to the sides. The pits are shaped like a coffee bean and the largest specimen seen was 3 cm wide and 3,5 cm long.

Discussion: This trail is a typical trilobite trail. It is like the trail figured by SEILACHER (1960a), as *Cruziana dispar* and also like the trail figured by SEILACHER (1955, Pl. 19) as *Rusophycus didymus* and *Crossochorda* from the Cambrian beds of the Salt range. The plough bands were made during the scratching activities of the legs toward a middle line. GOLDRING (1967) stated that trilobite traces are frequent in the neritic sandy facies of the lower Palaeozoic. None have been recorded from the Middle Devonian upward in the same facies. GOLDRING explains this phenomenon as a change in ecologic niche for the trilobites. In the Nehden siltstones trilobite trails are very common as can be seen from Text-Fig. 2. But here the normal type of neritic facies is not developed but rather a flysch-like sediment. GOLDRING's statement is still correct because apparently trilobites burrowing as benthonic animals have migrated since Lower Devonian time into deeper water with flysch-like deposition.

Dreginozoum cf. *nereitiforme* v. D. MARCK 1894

Pl. 39, Fig. 10

Description: Oval to rectangular patch-like structures on both sides of a median groove characterize this trail. Two patches of 7—8 mm length and 2—6 mm width ly opposite to each other along the 3 mm wide median groove. The maximum width of the trail is 2,5 cm and one of the two trails recovered from the Nehden siltstones is 5,5 cm, the other 11 cm long.

Discussion: HÄNTZSCHEL (1964) redescribed from the Campanian beds of Beckum in Nordrhein-Westfalen this trace fossil. The difference between this Cretaceous trail and the Devonian one, is that the patch-like structures on both sides of the median grooves seem to be somewhat rounder and that the width is only 1—1,5 cm. HÄNTZSCHEL thinks that these structures could have been a series of egg-cases of gastopods. The Devonian specimens are not of this origin. Small *Cruziana* passages and tube endings are imprinted on the less well preserved specimen. The trail therefore was only an impression on the sediment surface and not a solid structure. Therefore it could easily be worked over by the trails of other crawling benthonic animals. The trail was made by some unknown benthonic animals on the surface of the sediment.

Helminthopsis sp. HEER 1877

Pl. 39, Fig. 5; Textfig. 6, Fig. 4, 6

Simple not very regularly meandring tracks (width 1—4 mm). In one case a groove mark is intersected by a trail so this has been surely made on the sediment surface (Pl. 39, Fig. 5). The trails never touch each other. RABIEN (1956) gives the description of similar trails from the Hemberg and Dasberg siltstones of the Waldeck Syncline. Worm-like animals and gastropods could have been the producers of this trail.

Irregularly shaped trails

(Textfig. 6, Fig. 5; Pl. 38, Fig. 6)

There are two different types. The first is an irregularly coiled and winding trail branching irregularly. The trail crosses below or above and also through itself. Width 1,5 mm.

The trail (Textfig. 6, Fig. 5) can be seen in connection with star-like tracks and possibly is made by the animal also responsible for the star tracks. *Nereis* in the intertidal flats of the North Sea also produces star-like tracks at the end of its burrows, but also irregularly winding and coiled trails, when moving away from the burrow on the muddy sediment surface. If it crosses its own old course it may cut through it or dig down below it or put a mud bridge on top of the old trail. Possibly this trail was made under a very shallow sand cover at the mud-sand interface, so that the sand of the filling could be mixed with mud in the groove just formed by crawling and thus an irregular appearence was formed. If sand was present at all, there was probably only a thin veneer of it and it was reworked or only preserved in pits when the silt bed was deposited.

The second type is a large irregular winding trail, between 1,7 and 3 cm wide (Pl. 37, Fig. 6). The depth of the larger trail is 1,8 cm. It is the largest trail observed on the Nehden siltstone soles of Barmen. The trails were either made irregularly in calm water or in one case during the action of the current emplacing the silt bed (Pl. 37, Fig. 6). The cut specimen of the latter shows clearly that the basal sediment layers in the trail are disturbed and a ridge of fine sand was built up by the current behind the trail. The animal had plowed almost perpendicular to the current direction across the sediment surface. The side of the trail facing the current is overhanging or vertical to the deepest part of the trail. The other side is sloped shallowly and shows fluting. The trail must have been made by a rather large benthonic organism. It is the youngest trail on that particular sole disrupting all other trails and was made, while the deposition of the siltstone was going on. The parallel laminations of the lower part of the silt bed are parallel to the sediment surface, but form a small hill behind the downcurrent side of the trail.

Star tracks

Textfig. 6, Fig. 7; Pl. 39, Fig. 3, 4

Description: Branching, round, 1—3 mm thick tracks go off from a central point. Branching is Y-shaped, the thickness of the trail always remaining nearly the same. Between the branches anastomosing is also present sometimes forming an irregular network so that the center of the star track is difficult to detect.

Discussion: NATHORST (1881) described star tracks made by the annelids *Glycera alba* and *Gonidia maculata*, which live on the muddy bottom of the North Sea at a depth of 15 feet. *Nereis*, a polychaete worm, also produces star-like feeding tracks on the intertidal flats of the North Sea. The tracks of these worms are made around the ending of the subsurface burrow. The animal crawls some distance from the burrow on the sediment surface, then retreats into the burrow and crawls again in another direction. It may crawl some way from the burrow, then only retreat part of the distance to the burrow and change direction, thus using the portion of the trail close to the end of the subsurface burrow several times. The track was made on the sediment surface, as can be seen in cut silt beds, in which the grooves produced by the worm-like animal were filled by renewed deposition. Never have burrows been found extending into the silt and never has lamination above them been disrupted.

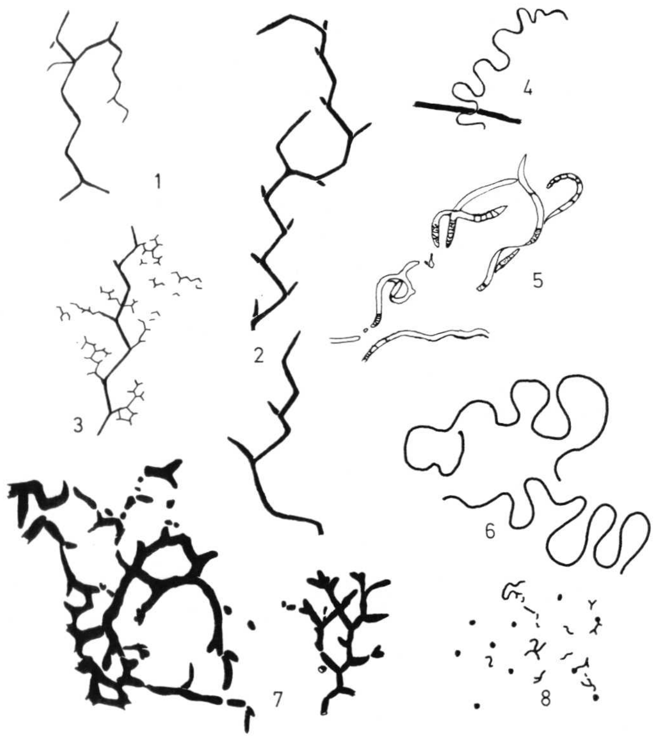
Tube endings and irregularly winding short trails

Textfig. 6, Fig. 8; Pl. 39, Fig. 2

Description: Round pits more or less regularly dispersed over many soles measuring 1—1,5 mm in width. Sometimes they are connected with 0,5—1 mm thick, short, branched, or unbranched, iregularly winding trails but also occur without them. Trails are found on many surfaces without pits.

Discussion: The pits are probably the casts of burrow endings made by worms, small arthopods, or gastropods. Mostly the pits are well preserved and are only rarely fluted. They often occur on current lineations, but have not been found to interfere with flute casts. The irregular winding and branching trails connected with the pits have been found in a large sharply incised groove mark. They continue from the adjacent sediment surface down the sides and along the bottom of the mark disrupting longitudinal scratches at the floor. This is evidence that the pits and trails were formed on the surface of the clay. Sawed specimens also reveal that tubes never continue into the silt and also narrow burrows have never been observed within the silt. The pits show that they were originally round depressions on the mud surface, which have been filled with sand and later sometimes covered with a very thin clay layer and finally by the silt bed. The tube endings therefore were made before the final deposition of the siltstone and after the first current had shaped the sediment surface. It is possible that some of the short thin trails and some of the pits are remains of original burrows washed out by the currents but no proof, by such evidence as, for example, better preservation of trails in the shallow longitudinal ridges than in the grooves or vice versa, could be found. The trails are always alike on different current marks at one sole.

Thin trails have also been found on the bedding planes of shale with *Chondrites* burrows. The pit and trail traces look very similar to the pit and trail system the gastropod *Hydrobia* produces on the muddy surfaces of the intertidal flats observed near Yerseke, Zeeland.



Textfig. 6. Surface trails made by a variety of animals:
1.—3. *Belorhaphe protophaleodictyon*
4. *Helminthopsis*
5. Irregularly coiled and winding trail
6. *Helminthopsis*
7. Star-like tracks
8. Irregularly branching narrow trails and tube endings.

Discussion of results

All trace fossils from the Nehden siltstones were made on the mud surface possibly sometimes at a sand mud interface, when the sand formed only a thin veneer and, if it was there at all, it must have been removed by erosion during the emplacement of the silt bed. Like EINSELE (1936b) I have also not been able to find burrows going through siltstone layers. However, the emplacement of the silt bed was not so rapid that the animals living on the surface were unable to keep up with sedimentation. Evidence for this are rare passages and resting tracks found within the silt beds, oriented parallel to the bedding plane. Burrows through the silt bed were not constructed, because escape burrows were not necessary. Burrowing animals were not able to construct postdepositional burrows at the silt-mud interface after deposition of the silt from above.

The same trace fossils are preserved on the top of the silt bed as on the sole of it, only the preservation is not as good on top. But the relative abundance of trace fossils here is the same as on the soles. Penetration of the silt bed from above does not occur except by the shallow burrows of trilobites. Not one trail could be found on the soles that was made after deposition of the silt bed. This is in opposition to EINSELE (1963b) who interpreted all trace fossils from the Nehden siltstones as predepositional with few exception that were postdepositional. Sections of all types of trails never revealed any disrupted laminations within the silt bed.

SEILACHER (1967b) stated that the Upper Devonian flysch deposits at Barmen are only atypical as flysch in one respect, the origin of the sediment. It was not derived from an orogenic belt, but from a stable foreland. Also EINSELE (1963b) thinks that this sequence is a typical flysch, because it was deposited in a geosyncline. SEILACHER (1967b) stated that in other respects, including the trace fossil fauna, it conforms to the flysch definition. In my opinion the trace fossil fauna certainly does not fit the picture given by SEILACHER (1958, 1962, 1963, 1964a, 1967b) for flysch deposits which is fully accepted by the present author. Complicated feeding burrows and regular parketting trails made by mud eaters in the sediment are typical for flysch deposits. They are absent from the Nehden siltstones. The trace fossil fauna here resembles more the *Cruciana* assemblage of SEILACHER (1963, 1964a). He reported from the shallow littoral facies. *Cruziana* communities are typical for epicontinental environments as demonstrated by SEILACHER (1967) in Palaeozoic rocks from Northern Iraq, the Oslo region, and the Appalachian system. GOLDRING (1967) reports the occurrence of trilobite trails from shallow-water facies only. Resting tracks, short, shallow burrowing trails, and feeding trails, constructed on the surface are most common in the Nehden siltstones.

The trace-fossil fauna does not answer to the flysch definition, but the rock facies does. According to BOUMA (1962), PLESSMANN (1962), and EINSELE (1963a) the Barmen Nehden siltstones are deposits of turbidity currents, showing graded bedding, the full BOUMA sequence, and all other features typical for flysch. Consistent transport directions as measured by PLESSMANN (1962) and EINSELE (1963a and b) at Barmen are also typical for flysch deposits.

The deposition of silt beds according to KUENEN (1968) was rapid. The sandy layers of the flysch were deposited instantaneously by turbidity currents, each bed in its entire thickness in a matter of hours or less. In the Barmen sequence convolute lamination gives proof of rapid deposition but sedimentation was not turbulent and quick enough that for benthonic animals there was no need to escape, and so they managed to stay on the surface.

Between deposition of the silt beds and currents producing the current marks on the mud surface, there was enough time in most cases for benthonic animals to produce a profusion of tracks and trails. Current action in this sequence of flysch-like rocks cannot therefore be connected with turbidity currents alone, for the currents forming flute marks, groove marks, and prod marks did not carry a suspension of silt and clay that settled immediately after formation of the marks. The currents that swept the bottom only carried little sand or no sediment at all. Most surprising in this respect is the fact that currents with and without sediment load came from the same direction, as indicated by the slight change in direction of different sets of groove and prod marks. Also marks on the sole show the same direction as current ripple structures (EINSELE, 1963b). Therefore some connection must have existed between the currents with sediment load and those without sediment load. Gravity pull of a loaded turbidity current cannot be the only mechanism for currents on the muddy bottom of the Nehden Sea.

The trails on the current marked mud surface were made in completely slack water. Proof for this is the complete absence of rheotactic orientation of the rest marks and the passages. That means that before the silt bed was deposited and after the first current action, currents must have died down completely. Sometimes a very fine clay film is developed between the small amount of sand brought down by the first current action and the silt and fine sand carried in by the current emplacing the silt bed. But greater amounts of clay have not settled during this time even though currents must have picked up a considerable load from the mud surface during scouring. EINSELE (1963a) thinks that the current marks developed on the Nehden siltstone soles must have been formed in water moving faster than 1 m/sec. The emplacement of the silt bed later must have taken place in most cases without destruction of the trails, possibly owing to the presence of a thin veneer of sand on the mud surface, which was removed except in pits preventing the trails from destruction. The normal, flysch-depositing currents were erosive as KUENEN (1968) stated. He thinks that the original thickness of pelagic deposits was in most cases three or four times the amount one now measures. For the Barmen Devonian the degree of erosion cannot be evaluated, but erosive forces were strong as indicated by the current marks. Erosion was not due to turbidity currents here.

The mud below the silt beds was laid down in quiet water. No burrowing activity has been observed within it. In contrast to the investigations of RABIEN (1956) at the Waldeck Syncline, a rich fauna of planktonic animal remains can be found in the shales between the silt beds at Barmen. Some layers are covered by tests of planktonic ostracods. Cephalopods are very common and the tests of bactritids and orthocerids never show orientation due to current action. The distribution of the fossil remains is random on the bedding planes. The only certain benthonic animal remains are those of blind trilobites. Their exuvia are preserved in "SALTER"-position. Even a weak current would have disturbed the position and picked up the light tests left by the trilobites. If the shales were deposited as slowly as in similar recent sediments like in the Adriatic Sea or in the Southern California Basin, only 7—10 cm of shale in 1000 years would have been accumulated (KUENEN, 1968). Thus the tests of animals were exposed for a long time on the surface without disturbance by current action. No burrowing activity of benthonic animals, such as those preserved on the silt soles, could have occurred. Burrowing or browsing by animals would have changed the "SALTER"-position of trilobite tests and orientation of cephalopod tests parallel to the bedding plane, as would the action of currents.

The only possible kind of environment would be with very little or no oxygen content in the water and in the sediment. The pyritic preservation of the inner whorls of goniatites indicates reducing conditions within the sediment. The conditions for life on the muddy floors of the Nehden sea must have been similar at times to the one envisaged by KUENEN (1968) for the depositional environment of flysch such as darkness, rather low temperature, normal salinity, insignificant currents, a continuous, slow rain of lutum, a low supply of organic material, low oxygen supply, and anaerobic conditions in the sediment. When currents intruded, they could not uncover burrows from the Nehden muds, because there were none present. This explains the difference between a typical flysch trace-fossil fauna, in which uncovered burrows were present, and the Nehden trace fossil fauna, which has no uncovered burrows, because animals were unable to produce them in the eroded mud.

Activity of benthonic animals coincided with the current activity that carried the oxygen necessary for life. After currents had swept the muddy surface, the oxygen supply was high enough to support a rich, benthonic life. In the lower Cypridinen-Schiefer below the Nehden siltstones a rhythmic change from fine-grained dark shale to silty light shale is developed in the magnitude of a few centimeters. Sometimes if the silt content is somewhat higher, trace fossils can be observed on the soles and in the thin silty layers. In these silty layers, body fossils can rarely be found but in the light shale above them, *Chondrites* burrows are sometimes present and ostracod and cephalopod tests are concentrated in burrows. Here and in the silty shales, the living conditions must habe been improved for benthonic life, just like shortly before the emplacement of the silt beds further up in the sequence. The shales above the silt beds in the Nehden siltstone sequence are also burrowed and commonly narrow straight or winding trails are observable on the bedding planes. The living conditions on the floor of the Nehden sea therefore must have changed within regular periods from poor oxygen supply to high oxygen supply. The oxygen supply on the Nehden sea bottom is closely related to current activities, reflected in the grain size of the sediment. Currents must have brought water rich in oxygen down to the floor and, when current action ceased for a long time, the oxygen supply decreased so far that life was impossible or barely possible. RABIEN's reconstruction of the Nehden depositional conditions are true only for some periods, when oxygen supply was low.

Results

It is shown that the trace fossil fauna in the Nehden siltstones is not of a flysch type. Complicated burrows typical for flysch trace fossils were not constructed in the muddy sediment, because the low oxygen supply did not permit settlement and burrowing by benthonic animals in and on the sediment before the onset of currents. The trace-fossil fauna shows much more resemblance to shallow-water, trace-fossil assemblages. The sedimentary features of the siltstones reflect emplacement by turbidity currents. The marks preserved on most soles are produced not by turbidity currents on the muddy surface, but by normal currents that swept the bottom before deposition of the silt beds. This kind of current was also present at periods in the lower "Cypridinen" shale, causing a cyclic change from dark to light sediment colour and from finer to coarser grains.

The tracks and trails preserved on the soles were made between phases of activity of normal currents and turbidity currents, during a time of slack water. The direction of currents was very consistent, regardless of whether they carried sediment load or not. The living conditions on the floor of the Nehden sea changed continuously between favourable and unfavourable to life. Oxygen content was low, when no currents were active, and it was high, when currents swept the bottom.

The body fossils in the Nehden deposits are mostly of planktonic animals, only trilobite remains are surely benthonic, because their tests are often found in a position, reflecting sloughing activity. Two types of trails have probably been made by trilobites, the others by worm-like or unknown benthonic animals.

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References

BANDEL, K. (1967): Trace fossils from two Upper Pennsylvanian sandstones in Kansas. — Kansas paleont. Contrib., **18**: 1—13.

BOUMA, A. H. (1962): Sedimentologie of some flysch deposits. — (Elsevier Pub. Comp.), Amsterdam.

DŻUŁYNSKI, S. & SMITH, A. J. (1963): Convulate lamination, its origin, preservation, and directional significance. — J. Sed. Petrol., **33**: 616—627.

DŻUŁYNSKI, S. & WALTON, E. K. (1965): Sedimentary features of flysch and grey-wackes. — Develop. in Sedimentol., vol. **7**: 1—274 (Elsevier Pub. Comp.), Amsterdam.

EINSELE, G. (1963a): „Convolute bedding“ und ähnliche Sedimentstrukturen im rheinischen Oberdevon und anderen Ablagerungen. — N. Jb. Geol. Paläont. Abh., **116**: 162—198.

—,— (1963b): Über Art und Richtung der Sedimentation im klastischen rheinischen Oberdevon (Famenne). — Abh. Hess. L-Amt Bodenforsch., **43**: 1—60.

GOLDRING, R. (1967): The significance of certain trace-fossil ranges. — The fossil Record, Geol. Soc., London: 37—39.

HÄNTZSCHEL, W. (1962): Trace-fossils and Problematica. — In Treatise Inverteb. Paleont., W: 177—245, New York.

—,— (1964): Spurenfossilien und Problematica im Campan von Beckum (Westf.). — Fortschr. Geol. Rheinld. u. Westf., **7**: 295—308.

KUENEN, P. H. (1968): Turbidity currents and organisms. — Eclogae geol. Helv., **61**: 525—544.

KÜHN-VELTEN, H. (1955): Subaquatische Rutschungen im höheren Oberdevon des Sauerlandes. — Geol. Rdsch., **44**: 1—25.

—,— (1968): Struktur, Orientierung und Richtung in sandigem Oberdevonsediment (Plattensandstein der Nehden-Stufe) des nördlichen Sauerlandes. — Fortschr. Geol. Rheinld. u. Westf., **16**: 239—268.

NATHORST, A. G. (1881): Om spăr af nägra evertebrerade djur M. M. och deras paleontologiska betydelse. — K. Svenska Vetenskaps-akad. Handl., **18**: 1—104.

PAECKELMANN, W. & FUCHS, A. (1928): Erläuterungen zur geologischen Karte, Blatt Hattingen. — Preuß. Geol. L.-Amt Berlin, Liefg. 274: 1—82, Berlin.

PLESSMANN, W. (1962): Über Strömungsmarken in Oberdevon-Sandsteinen des Sauerlandes. — Geol. Jb., **79**: 387—398.

RABIEN, A. (1956): Zur Stratigraphie und Fazies des Ober-Devons in der Waldecker Hauptmulde. — Abb. hess. L.-Amt Bodenforsch., **16**: 1—83.

RICHTER, RUD. (1920): Vom Bau und Leben der Trilobiten II. — Senckenbergiana, **2**: 23—42.

—,— (1937): Die „SALTER'sche Einbettung“ als Folge und Kennzeichen des Häutungsvorganges. — Senckenbergiana, **19**: 413—431.

—,— (1941): Risse durch Innenschrumpfung und Risse durch Lufttrocknung. — Senckenbergiana, **23**: 165—167.

SCHÄFER, W. (1962): Aktuo-Paläontologie nach Studien in der Nordsee. — (W. Kramer), Frankfurt a. M.

SCHINDEWOLF, O. H. (1926): Ein Wort über die Faziesverteilung im Oberdevonmeer. — Z. dt. geol. Ges., **78**.

SCHINDEWOLF, O. H. & SEILACHER, A. (1955): Beiträge zur Kenntnis des Kambriums in der Salt Range (Pakistan). — Abh. Akad. Wiss. Literatur, Mainz, math.-naturwiss. Kl., **10**: 373—399.

SCHMIDT, H. (1935): Die bionomische Einteilung der fossilen Meeresböden. — Fortschr. Geol. Palaeont., **12**: 1—154.

SEILACHER (1955): Spuren und Fazies im Unterkambrium. — In: SCHINDEWOLF, O. H. & SEILACHER, A.: Beiträge zur Kenntnis des Kambriums in der Salt Range (Pakistan). — Abh. Akad. Wiss. Lit., Mainz, math.-naturwiss. Kl., **10**: 373—399.

—,— (1958): Zur ökologischen Charakteristik von Flysch und Molasse. — Eclogae geol. Helv., **51**: 1061—1078.

—,— (1960a): Lebensspuren als Leitfossilien. — Geol. Rdsch., **94**: 41—50.

—,— (1960b): Strömungsanzeichen im Hunsrückschiefer. — Notizbl. hess. L.-Amt Bodenforsch., **88**: 88—106.

—,— (1962): Paleontological studies on turbidite sedimentation and erosion. — J. Geol., **70**: 227—234.

—,— (1963): Aportaciones al estudio de la facies Flysch. — Notas y. Comuns. Inst. Gesl. y Minero de Espana, **72**: 129—178.

—,— (1964a): Biogenic sedimentary structures. — In: IMBRIE, J. & NEWELL, N.: Approaches to Paleoecology (John Wiley & Sons).

—,— (1964b): Sedimentological classification and nomenclature of trace-fossils. — Sedimentology, **3**: 253—256.

SEILACHER, A. & HEMLEBEN, C. (1966): Spurenfauna und Bildungstiefe der Hunsrückschiefer (Unterdevon). — Notizbl. hess. L.-Amt Bodenforsch., **94**: 40—53.

SEILACHER, A. (1967a): Bathymetry of trace-fossils. — Marine Geology, **5**: 413—428.

—,— (1967b): Tektonischer, sedimentologischer oder biologischer Flysch. — Geol. Rdsch., **56**: 189—200.

SIMPSON, S. (1956): On the trace-fossil *Chondrites*. — Quart. J. Geol. Soc., **112**: 21—24.

WUNDERLICH, F. (1967): Die Entstehung von „convolute bedding“ an Platenrändern. — Senck. leth., **48**: 345—449.

Explanation of Plates

Plate 37

Marks and trails on siltstone soles of the Nehden siltstone at Barmen.

Fig. 1. Test of *Posidonia*, x 0,72.
Fig. 2. Cast of impression of a trilobite carapace on the mud surface, x 0,96.
Fig. 3. Impression of a goniatite test, x 1,2.
Fig. 4. Asymmetrical, flat flute cast with trails cutting across; in the upper left of the figure are groove marks preserved, x 0,9.
Fig. 5. Obstacle scour behind a goniatite test, x 1,2.
Fig. 6. *Belorhaphe* cutting across wrinkled surface and groove mark, x 0,6.
Fig. 7. Groove marks and round prod mark, x 1,2.
Fig. 8. Dessication cracks and short, irregularly winding trails, x 0,4.
Fig. 9. Groove mark with ridges on the bottom and prod marks. Tube endings and short irregularly winding trails are also preserved, x 0,9.

Plate 38

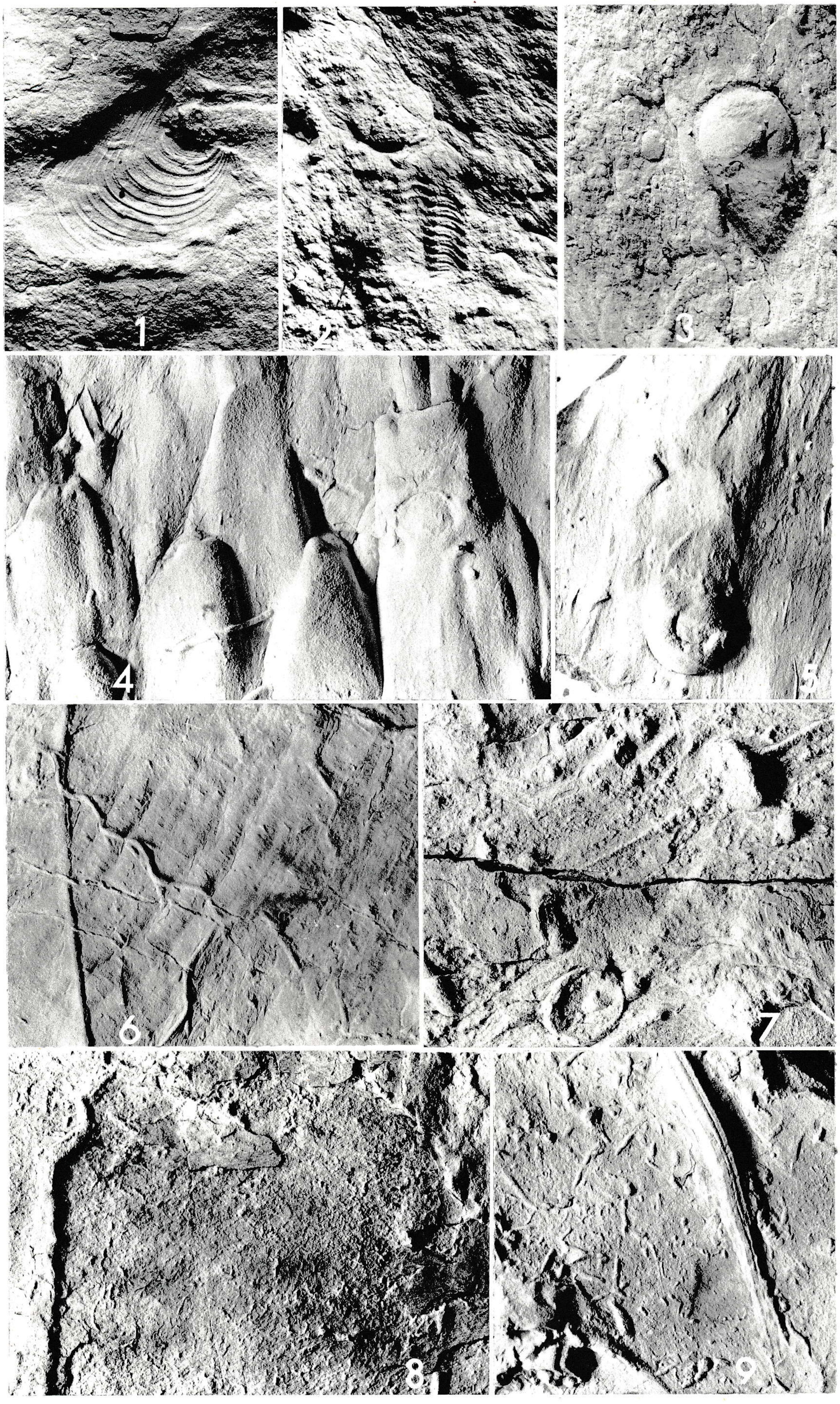
Marks and trails on siltstone soles from the Barmen Nehden sequence.

Fig. 1. Corkscrew flute marks with *Cruziana barmensis* passage cutting sharply across, x 0,6.
Fig. 2. *Belorhaphe protopaleodictyon,* wide and narrow passages in connection, x 1,2.
Fig. 3. *Cruziana* cf. *dispar* passage, x 0,8.
Fig. 4. Series of *Cruziana barmensis* resting tracks, x 0,72.
Fig. 5. Passages of *Cruziana barmensis* on a sole, showing longitudinal furrows and ridges and grooves and prod marks, x 0,96.
Fig. 6. Large irregularly winding trail, made during current action, showing fluting on the down-current side and overhanging or vertical appearance on the up-current side, x 06.

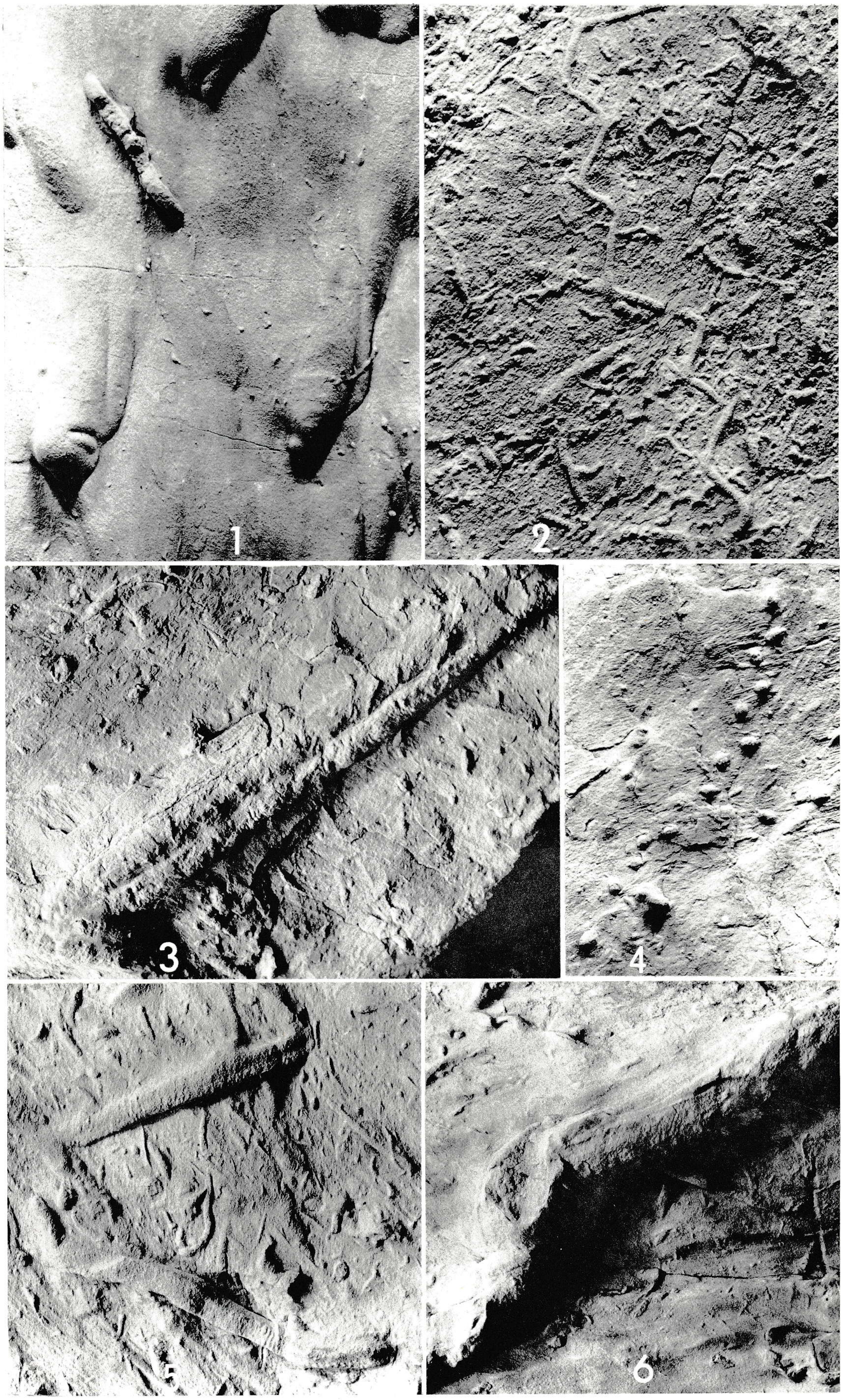
Plate 39

Marks and trails on the siltstone sole except Fig. 8, which was formed on the siltstone surface of the Barmen Nehden siltstones.

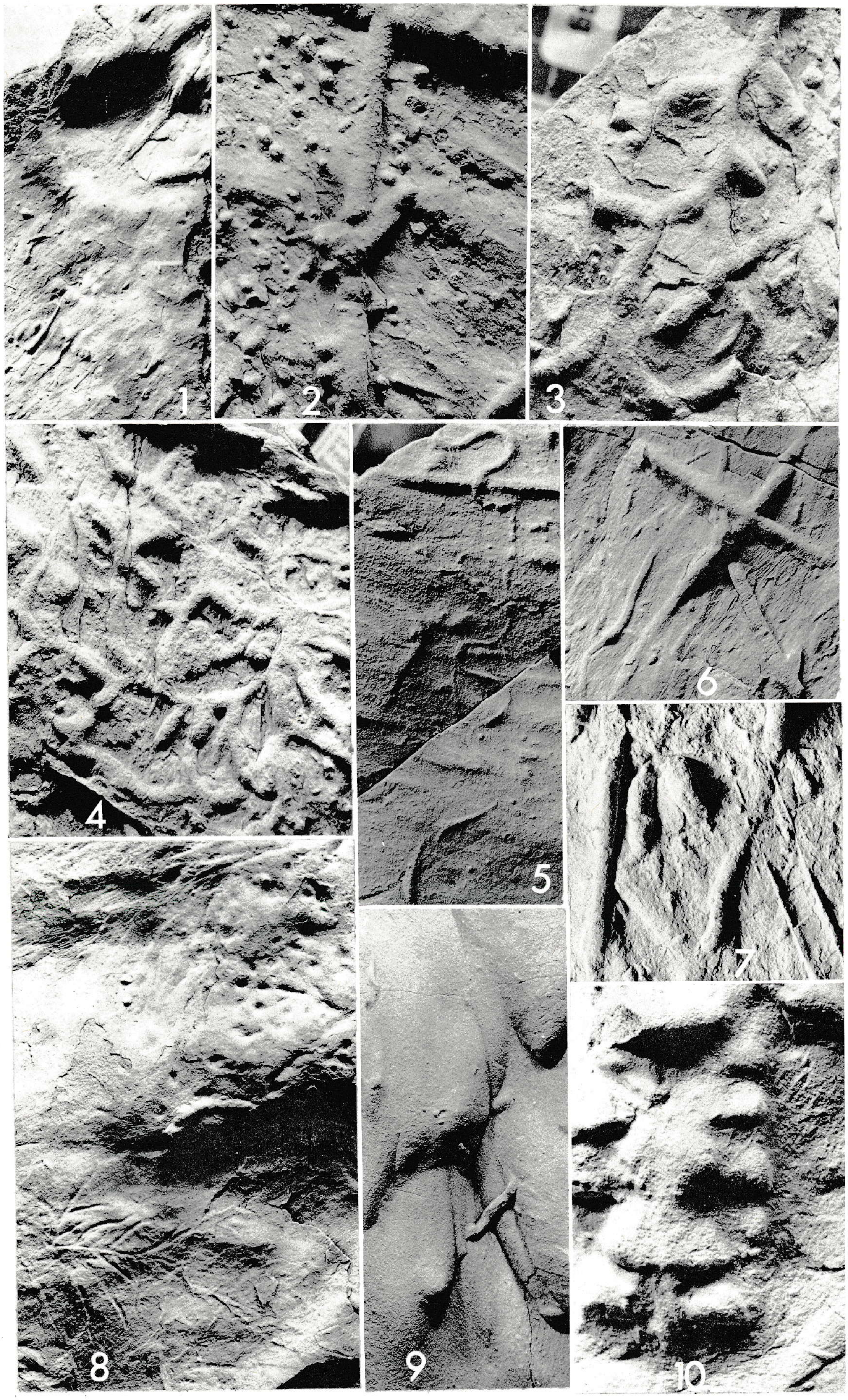
Fig. 1. Smooth surface changing into pitted surface. A passage of *Cruziana* cutting across a pit, x 0,86.
Fig. 2. Passage of *Cruziana* and round tube endings, x 1,2.
Fig. 3. Part of star-track showing Y-shaped branching, x 0,8.
Fig. 4. Star-track with anastomosing branches, x 1,2.
Fig. 5. *Helminthopsis* crossing groove mark, disrupting it, x 1,2.
Fig. 6. Three *Cruziana barmensis* passages cross each other, the younger always destroying the older, x 0,9.
Fig. 7. Resting mark of *Cruziana barmensis* and groove marks cutting across old *Cruziana* passage.
Fig. 8. *Chondrites* tunnel system penetrating the uppermost siltstone layers (upper part of figure) and *Chondrites* "twig system" constructed along silt-mud interface, x 0,9.
Fig. 9. *Cruziana barmensis* cutting from one flute cast to the next, x 0,6.
Fig. 10. *Dreginozoum* cf. *nereitiforme,* x 1,2.



K. Bandel: Trace fossils from the Upper Devonian Nehden Siltstones of Wuppertal-Barmen.



K. B a n d e l : Trace fossils from the Upper Devonian Nehden Siltstones of Wuppertal-Barmen.



K. Bandel: Trace fossils from the Upper Devonian Nehden Siltstones of Wuppertal-Barmen.