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TRACE FOSSILS FROM THE EOCENE KAYO FORMATION IN OKINAWA-SHIMA, RYUKYU ISLANDS, JAPAN

By

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Introduction and Acknowledgements

During the past decade, trace fossils have come to be known to occur from rather poorly fossiliferous basement rocks in South Kyushu and the Ryukyu Islands. Unfortunately, however, only a few paleontological studies on them have been published to date (KONISHI, 1963; HAYASAKA *et al.*, 1975).

As a part of the writers' serial study, the trace fossils from the Kayo Formation are described in the present article, with some remarks on the geologic setting and the mode of occurrence of them.

Here the writers express their hearty thanks to Professor Hakuyu OKADA of the Shizuoka University for his advices on classification of sandstone, and to Drs. Akira IWAMATSU and Hiroyuki OTSUKA both of the Kagoshima University for their suggestions on the geology of this area. Thanks are also due to Mr. Akihiko KAIHORI of the Ôyo Chishitsu Co., for his help in the field.

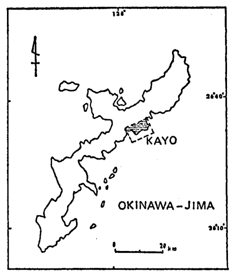

Fig. 1. Index map.

Geologic Setting of the Kayo Formation

The Kayo Formation, originally named by FLINT *et al.* (1959) as the Permian formaion conformably overlying the Nago Formation, is considered at present to be Eocene in age (KONISHI *et al.*, 1973) based on the common occurrence of *Nummulites* sp. therefrom, and is regarded to represent the Shimajiri Zone (Southeasternmost zone of the Shimanto Terrain). The distribution of the Kayo Formation has been known in the east-central part (type area) and the east coast area of the northern part of Okinawa-shima (HASHIMOTO *et al.*, 1976; OSOZAWA *et al.*, 1977).

Through the study on the Kayo Formation (FUKUDA *et al.*, 1978) developed in this type area, the following several points have been made clear. (1) The Kayo Formation is judged to contact with the underlying Nago Formation by an overthrust dipping

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towards NNW. (2) The Kayo formation, of which total thickness attains to 850 m, is composed of the alternation of quartz-rich, fine- to medium-grained sandstone and shale and subordinate intraformational conglomerates. (3) On the lower surface of sandstone beds are observed small-scale flute casts and various kinds of trace fossils, of which two species have been described by KONISHI (1963). (4) In the Kayo Formation developed in the present area, five successive units were discriminated (Fig. 3, Table 1) based on the litho-facies type such as the sandstone with the intraformational conglomerates and three types of sandstone-shale alternation - predominantly sandy, uniform and regular, or predominantly shaly. (5) Through the study on the composition of sandstone forming more than 10 cm thick bed in the Kayo Formation, thrity-six among the fourty-five examined samples were identified after OKADA (1971) as the feldspathic arenite, two quartz arenite and seven feldsapathic wacke. In average, the volume ratio of quartz is 63.6%, feldspar 26.3% and rock fragment 10.1%, respectively. Feldspars are represented mainly by orthoclase with subordinate microcline. Rock fragments are represented by a large amount of argillaceous sedimentary rock fragments with a small amount of volcanics. Biotite, sericite and calcite crystals are also recognized to occur. Average grain size in each slide of thin section ranges from 0.1 to 0.3 mm, and in general, grains are well-rounded and well-sorted.

In the present article, trace fossils from the Kayo Formation are described and discussed.

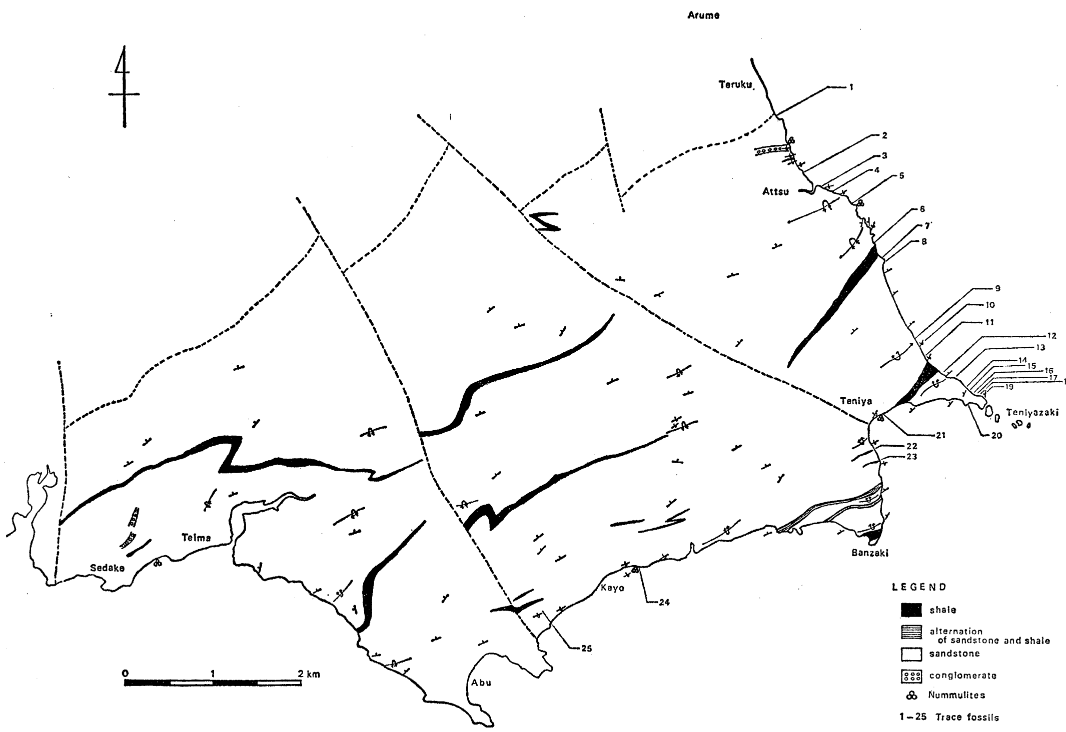

Fig. 2. Geologic map of the east-central part of Okinawa-shima, the type area of the Kayo Formation. (Numerals indicate the localites of trace fossils)

Table 1. Five successive units discriminated in the Kayo Formation.

Five successive units	Distribution	Thickness	Litho-facies
K_4 Sandstone-shale alternation -Predominantly shaly-	Sea-cliff about 700 m northeast of Teniyazaki	60 m	Sandstone beds (3–10 cm thick): fine-grained; provided with parallel laminations and current ripple lamina, and with straight current ripple marks on the upper surface of sandstone beds showing the ESE current direction; trace fossils are found on the lower surface of sandstone beds and within shale beds. Shale beds (5–10 cm thick)
K_3 Sandstone-shale alternation	Sea-cliff between Teniyazaki and about 700 m northwest of it.	170 m	Sandstone beds (30–60 cm thick): fine- to medium-grained; provided with parallel lamination and current ripple lamina; minute flute casts showing NE direction on the soles of sandstone beds; straight current ripple marks on the upper surface of sandstone beds showing the SW current direction. Shale beds (3–5 cm thick): Occasionally coarse grained-sandstone beds (50–100 cm thick) with parallel lamination of angular shale fragments and with nummulite fossils.
K_2 Sandstone-shale alternation -Predominantly sandy-	Sea-cliff between eastside of the Attsu river mouth and 1500 m southeast of it.	330 m	The lower part: medium- to coarse-grained sandstone beds (100–150 cm thick) with parallel lamination predominate. Rarely with small-scale slump structures and with thin granule conglomerate beds bearing nummulite fossils. The upper part: consists of several sedimentary cycles (20 to 50 m in thickness), each of which shows rather regular change in lithofacies from medium- to coarse-grained sandstone (100–150 cm thick) with parallel lamination to fine- to medium-grained sandstone (20–40 cm thick). Small-scale flute casts, load casts, ripple marks and trace fossils.
K_1 Sandstone intercalated with intraformational conglomerates	Sea-cliff between 500 m south of Teruku and west side of the Attsu -river mouth.	240 m	Lithofacies changes as follows (in descending order): medium- to coarse-grained sandstone provided with parallel lamination (thickness of each bed ranges from 100 to 200 cm) gradually increases in number of intercalation of conglomerate (thickness ranges from 150 to 550 cm) and changes again into medium- to coarse-grained sandstone with parallel lamination (60 to 100 cm in thickness of each bed). Thickness of conglomerates totals about 65 m. Intraformational conglomerates, of which internal structure represents grading, include the pebbles of sandstone (rounded), shale (angular), black siliceous shale (subrounded), chert (subangular), limestone (subrounded) and orthoquartzite (rounded). Nummulite fossils are often found from the matrix of conglomerates (Konishi *et al.*, 1973).
K_0 Sandstone-shale alternation	Sea-cliff 250 m south of Teruku	30 m	Sandstone beds (20–50 cm thick): fine- to coarse-grained; rarely attain to 100–150 cm in thickness; thinning upwards in general aspect; rarely with trace fossils on their lower surfaces. Shale beds (1–20 cm thick)

Table 2. Trace fossils from the Kayo formation.
(Numerals correspond to those in the figs. 2 and 3)
(◎○: Ill-preserved and undistinguishable specimens.)

TRACE FOSSILS		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
SPIRORHAPHE SP.		○						○			○		○							○					○	
SPIRORHAPHE SP. (A)																						○				
SPIRORHAPHE SP. (B)									○										○			○				○
SPIRODESMOS SP.									○																	
SPIRODESMOS SP. (A)					○																				○	○
SPIRODESMOS SP. (B)																						○				○
HELMINTHOIDA SP. (C)							○			○	○	○		○		○	○	○			○				○	○
HELMINTHOIDA SP. (A)								○	○											○		○	○	○		
HELMINTHOIDA SP. (B)																				○						
HELMINTHOPSIS SP.				○		○			○										○					○		○
COSMORHAPHE SP.																						○	○		○	○
BELORHAPHE SP.			○						○																	
PALEOMEANDRON SP.																						○				
PALEODICTYON SP.					○				○													○				
FEEDING BURROW													○											○		○
MISCELLANEOUS									○						○					○						○

Distribution of Trace Fossils (Table 2)

The distribution of trace fossils in each locality is shown in the table 2, in which all the figures, except for the feeding burrow, were sketched from the lower surface of sandstone beds.

Description of Trace Fossils

Ichnogenus *Spirorhaphe* FUCHS, 1895

Spirorhaphe sp. a
Pl. 1, fig. 12; table 2.

A set of parallel strings dextrally coiled; coil nearly circular in outline; the largest diameter of coil measures about 14 cm and the shortest one about 9 cm. Only a single specimen is in the collection.

Spirorhaphe sp. b

A set of parallel strings sinistrally coiled; coil nearly circular in outline; strings 0.8–1.8 mm thick; diameter of spiral ranges from 1.1 (shortest) $\times$1.5 cm (longest) to 12$\times$17 cm. In general, the thicker the string, the bigger the spiral.

Remarks: - This species closely resembles *Spirorhaphe* sp. illustrated by HÄNTZSCHEL (1975, fig. 65, 1a, 1b). *Spirorhaphe concentrica* KATTO described by KATTO (1964) from the Eocene Naharigawa Formation in Shikoku differs from the present species in having smaller diameter of spiral and thicker string. Five specimens are in the collection.

Ichnogenus *Spirodesmos* ANDRÉE, 1920
Spirodesmos sp. a

String sinistrally coiled from the center outwards; coils rather regular in shape; string 0.8–1.5 mm thick; diameter of sprial rather variable, ranges from 1.6$\times$2.4 cm to 6.6$\times$8.9 cm.

Remarks: - This is closely similar to *Spirodesmos* sp. illustrated by HÄNTZSCHEL (1975, fig. 64, 6b) in having regularly coiled outline. Five specimens are in the collection.

Spirodesmos sp. b
Pl. 1, fig. 11; table 2.

String dextrally coiled from the center outwards; string 0.5–0.9 mm thick; diameter of sprial ranges from 2.2$\times$2.4 cm to 2.8$\times$3.4 cm. Four specimens are in the collection.

Ichnogenus *Helminthoida* SCHAFHÄUTL, 1851
Helminthoida sp. a
Pl. 1, fig. 13; table 2.

String 1.75–2.80 mm thick, closely meandering with interspace of 1–2 mm; meandering string nearly straight and parallel; the width of meanders 6–11 cm.

Remarks: – This type closely resembles *Helminthoida* sp. illustrated by HÄNTZSCHEL (1975, fig. 44, 1c) in general appearance. Six specimens are in the collection.

Helminthoida sp. b
Pl. 2, figs. 1 and 2.; table 2.

String 1.98–2.84 mm thick, closely meandering with interspace of 4–6 mm; meandering string concentric or U-shaped and parallel; width of meandering 11–12 cm.

Remarks: – Two specimens are in the collection. One of them has a close alliance to *Tosahelminthes curvata* KATTO (1960) described from the Eocene Naharigawa Formation in Shikoku. Another specimen is somewhat similar to the Recent deep-sea trails described by BOURNE *et al.*, (1965).

Helminthoida sp. c
Pl. 1, fig. 5.; table 2.

String 0.8–1.2 mm thick; not so closely meandering; interspace about 1 cm; width of meanders 1–3 cm.

Remarks: – This is the most common type of trace fossil in the Kayo Formation.

Ichnogenus *Helminthopsis* HEER emend. SACCO, 1888
Helminthopsis sp.
Pl. 1, figs. 9 and 10; table 2.

String 0.7–2.5 mm in thickness; simply curving in S-shape; size of specimen rather variable.

Remarks: – Relatively large specimens with the string of 2.0–3.0 mm resemble *Helminthopsis* sp. illustrated by HÄNTZSCHEL (1975, fig. 44, 2b). The specimens of this species are often found in a crowded occurrence.

Ichnogenus *Cosmorhaphe* FUCHS, 1895
Cosmorhaphe sp.
Pl. 1, figs. 1 and 2; table 2.

Smaller type: string 0.65–1.2 mm in thickness; wave length of S-shaped cruve of the primary level about 5 mm.

Larger type: string 2.5–3.5 mm in thickness; wave length of S-shaped curve of the primary level 1.5–2.5 cm; that of the secondary level 3–6 cm; depressed S-shape in outline.

Remarks: – The specimens of which string is rather thin resemble *Cosmorhaphe sinuosa* (AZPEITIA) described and illustrated by KSIAZKIEWICZ (1970, fig. 2a), while the specimens with rather thick string resemble *Cosmorhaphe helmintopsida* (SACCO) also illustrated by KSIAZKIEWICZ (1970, fig. 2c).

Ichnogenus *Belorhaphe* FUCHS, 1895
Belorhaphe sp.
Pl. 1, fig. 6; table 2.

String 1.0 to 1.5 mm in thickness; zigzag-shaped with node-like projection at the obtuse angle formed by regular alternating of straight lines of 3 and 4 mm length.

Remarks: – Two specimens are in the collection. The present specimens are similar in shape to *Belorhaphe* sp. illustrated by HÄNTZSCHEL (1975, fig. 44, 2b) and to *Belorhaphe zickzack* (HEER), but the latter two species represent more regular zigzag forming acute angles.

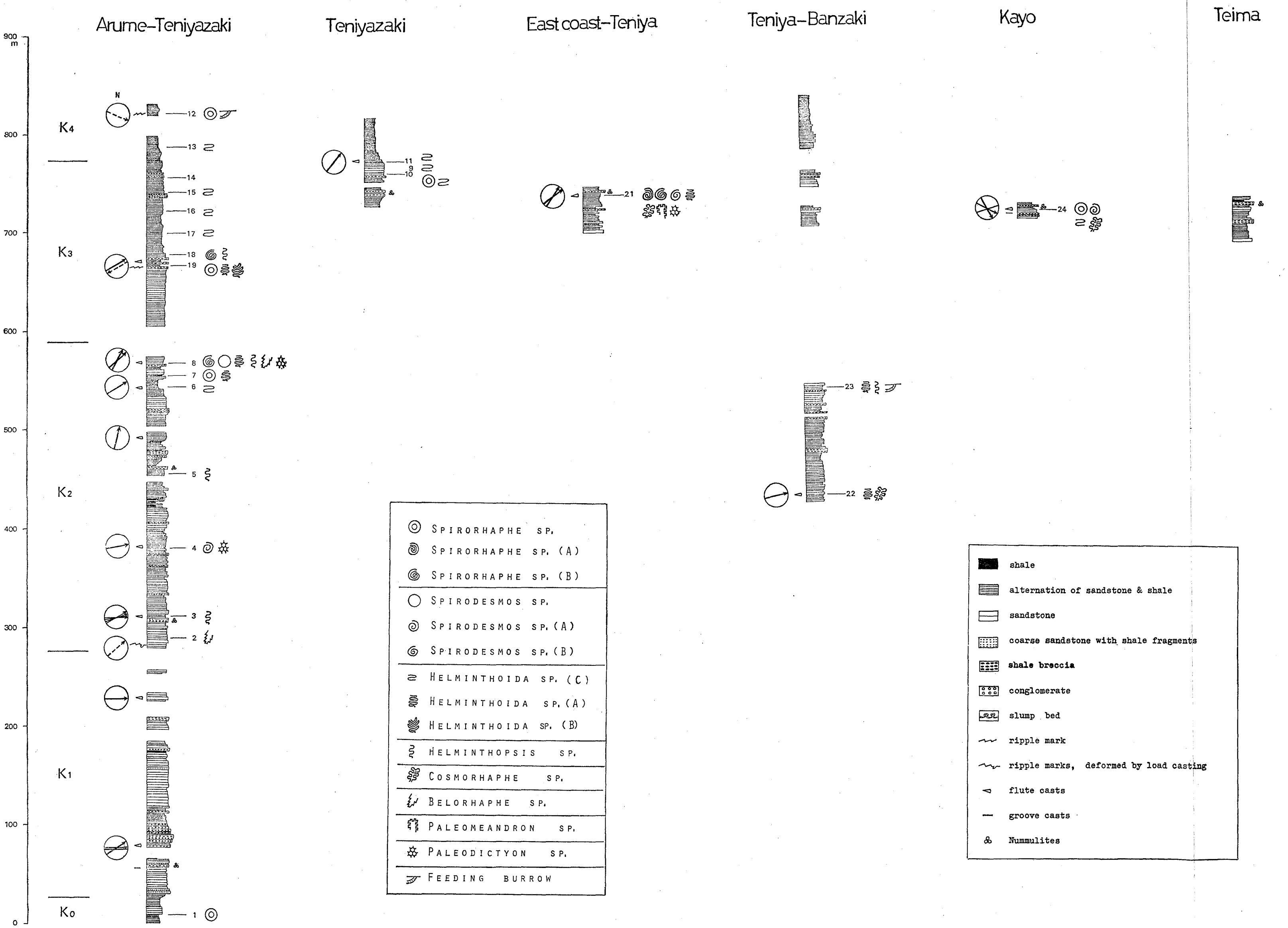

Fig. 3. Relation of the occurrence of trace fossils and the paleo-currents to the vertical change of lithofacies of the Kayo Formation.
(◎○: Ill-preserved and undistinguishable specimens.)

Ichnogenus *Paleomeandron* PERUZZI, 1888
Paleomeandron sp.
Pl. 1, figs. 7 and 8; table 2.

String 0.75 mm in thickness, irregular S-shaped meanders of straight fractions of about two millimeters length.

Remarks: – Only a single specimen is in the collection. The present specimen closely resembles *Paleomeandron elegans* PERUZZI illustrated by KSIAZKIEWICZ (1970, fig. 3d) in having regular, small-scale meandering.

Ichnogenus *Paleodictyon* MENEGHINI, 1850
Paleodictyon sp.
Pl. 1, figs. 3 and 4; table 2.

Honey-comb-like network structure, pentagonal or hexagonal meshes.

Remarks: — Five specimens are in the collection, in which three types are discriminated by difference in size.

Type a (pl. 1 fig. 3): Thickness of wall of network 0.9–1.1 mm; size of mesh 6×8 mm, mesh flattened in shape; partly destroyed by stirring at the time of deposition. KONISHI (1963) compared this type with *Paleodictyon majus* MENEGHINI, but it may be better to compare it with *Paleodictyon carpathicum* MATYASOVSZKY (KSIAZKIEWICZ, 1970, pl. 4n-g).

Type b (pl. 1 fig. 4): Wall thickness 0.8 mm, size of mesh 1.1×1.8 mm; slightly flattened, small-scale network. This type is closely similar to *Paleodictyon intermedium* KSIAZKIEWICZ (1970, pl. 4g) in having rather thick wall compared with mesh zise.

Type c: Wall thickness 0.5 mm, size of mesh 2.6×3.2 mm. This type resembles *Paleodictyon strozzi* MENEGHINI (KSIAZKIEWICZ, 1970, pl. 4h) in having rather thin wall compared with mesh size.

Mode of Occurrence of Trace Fossils

The relations of the kinds of trace fossils to thickness and internal structure of sandstone beds and to the directions of source of materials and of bottom current at the time of their deposition were examined.

The sandstone beds of the Kayo Formation are classified into the following four types (after BOUMA, 1962).

1) The medium- to coarse-grained sandstone beds starting with the "a" part. These are characterized by the development of very thick "b" part and lacking in the "c" part. In the granule conglomerates or the intraformational conglomerates, however, the "a" part is usually thicker than the "b" part.

2) The fine- to medium-grained sandstone starting with and characterized by the "b" part. As shown in the fig. 4, the sandstone beds of this type range from several centimeters to 150 cm in thickness, and are characterized by the development of

Table 3. Measurements of trace fossils.

Trace fossils	Width of threads (in mm)	Diameter of spirals (in cm)
Spirorhaphe sp.	2.00	9×14
	1.80	12×17
	1.50	5.0×6.7
	1.32	4.6×4.8
	1.20	2.5×3.7
	1.10	7×10
	1.00	4.4×5.4
	0.80	1.1×1.5
Spirodesmos sp.	2.15	6.6×8.9
	1.50	2.3×3.6
	1.40	5.3×7.1
	1.20	2.7×4.0
	1.00	1.6×2.4
	0.90	2.8×3.4
	0.80	2.4×3.2
	0.80-0.40	2.1×4.0
	0.65	2.8×4.1
	0.50	2.2×2.4
Helminthoida sp.	2.84	
	2.80	
	2.78	
	2.63	
	2.50	
	2.30	
	1.98	
	1.95	
	1.75	
	1.20-1.25	
	1.18	
	0.90	
	0.80	
Helminthopsis sp.	0.75	
	0.60	
Cosmorhaphe sp.	3.49	
	3.45	
	3.35	
	2.94	
	2.84	
	2.45	
	1.20	
	0.75-0.80	
	0.75	
	0.65-0.80	
Paleomeandron sp.	0.75	
Belorhaphe sp.	1.45	
	1.00	

	Thickness of wall (in mm)	Diameter of mesh (in mm)
Paleodictyon sp.	1.10	6.1×9.3
	0.90	6.2×7.4
	0.80	1.1×1.8
	0.50	2.6×3.2

numerous parallel laminations. On the lower surfaces of sandstone beds, flute casts and groove casts are often observed.

3) The fine sandstone beds less than 20 cm in thickness. This type of sandstone bed is identified as the "Tc-e" of the BOUMA's model and usually provided with current ripple laminations and ripple marks.

4) The sandstone beds starting with the "d" part. This type of sandstone bed is rather poor in development in the Kayo Formation. The beds showing the "Td-e" of the BOUMA's model are rarely found.

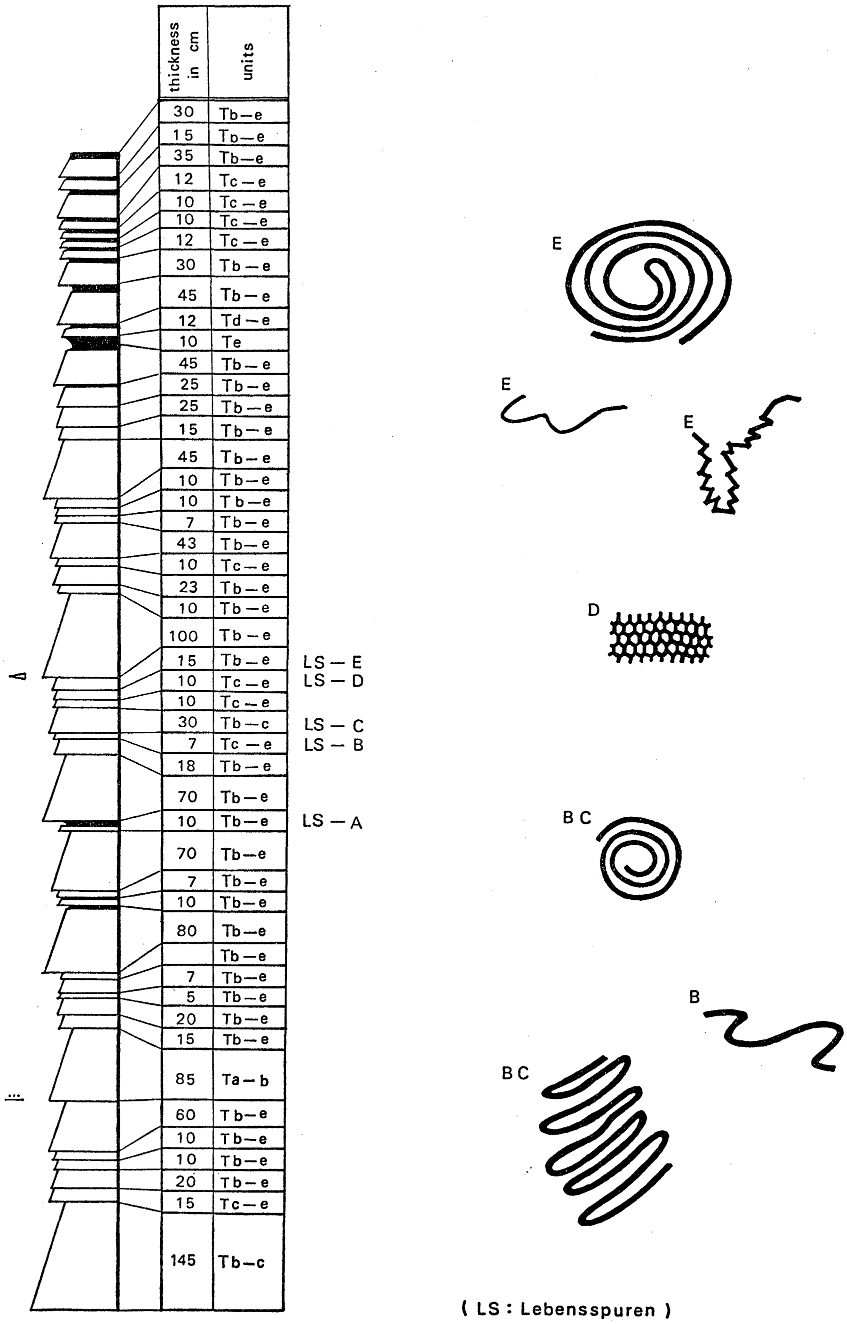

Fig. 4. An example showing the relation between the BOUMA's model and trace fossils.

The features of sandstone beds bearing trace fossils are summarized as follows:

Trace fossils	Features of sandstone beds bearing trace fossils
Spirorhaphe sp.	Tb-e (10–30 cm thick), Tc-e (17 cm thick), fine-to medium-grained sandstone
Spirodesmos sp.	Tb-e (10–30 cm thick), Tc-e (7–17 cm thick) Td-e (4 cm thick), fine-grained sandstone.
Helminthoida sp.	Tb-e (20–30 cm thick), Tc-e (4–7 cm thick) fine-to medium-grained sandstone.
Cosmorhaphe sp.	Tb-e (8–30 cm thick), Tc-e (17 cm thick) fine- to medium-grained sandstone.
Belorhaphe sp.	Tb-e (8–25 cm thick), fine-grained sandstone.
Paleomeandron sp.	Tb-e (8 cm thick), fine-grained sandstone.
Paleodictyon sp.	Tb-e (8–30 cm thick), Tc-e (10 cm thick), fine-grained sandstone.

From the above table, it can be reasonably say that the most of trace fossils from the Kayo Formation occur on the lower surface of sandstone beds being less than 30 cm in thickness and representing the Tb-e or the Tc-e types of BOUMA's model. Even in the case of sandstone beds thinner than 30 cm, trace fossils are usually absent when flow marks, such as flute casts, are markedly developed.

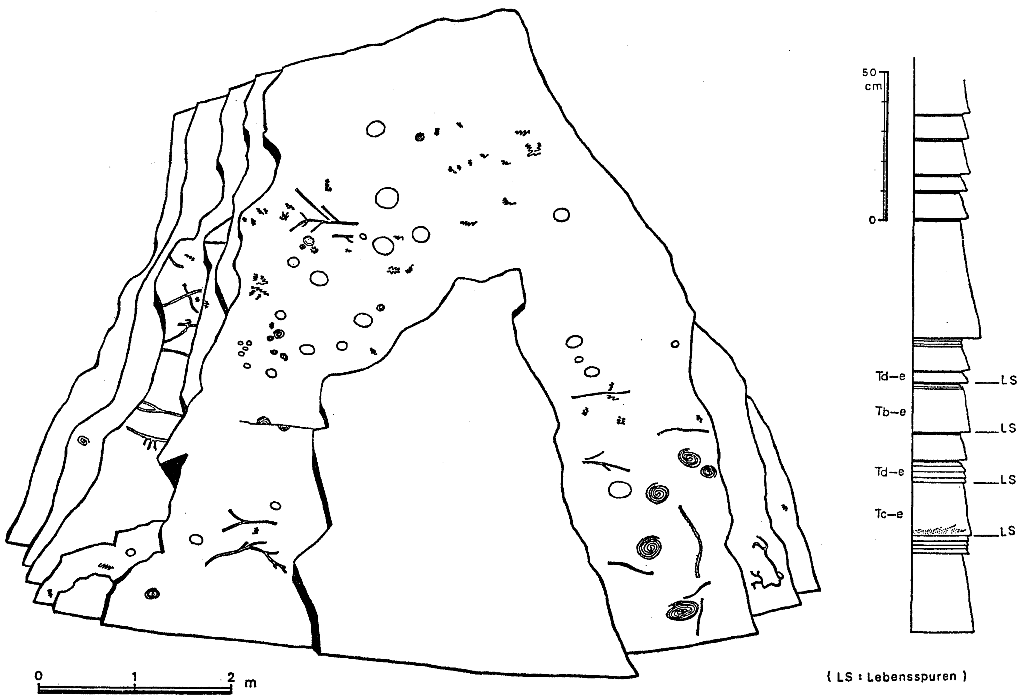

Fig. 5. Mode of occurrence of trace fossils at the locality no. 25.
Dual spiral: *Spirorhaphe* Circle: *Spirodesmos*
Meandering line: *Helminthoida* or *Helminthopsis*
Branching dual line: feeding burrows

The rather small-scale trace fossils having rather thin string are restricted in occurrence to fine-grained sandstone, while rather large-scale ones having rather thick string (1.5–3.0 mm thick) occur not only on the fine-grained but also on the medium-grained sandstone beds.

To scrutinize the relation of source of supply of turbidite and the direction of bottom current to trace fossils, even the minute indications of paleo-currents were observed on the outcrops (figs. 5, 6 and 7). In the fig. 6, the specimens of *Cosmorhaphe* sp. seem to have no definite relations to paleo-current direction. However, the specimens of *Helminthopsis* sp. and *Belorhaphe* sp. seem to be made by the movement of animals oblique to current direction. On the other hand, the fig. 7 shows that the directon of current ripple marks almost corresponds to that of the crowded occurrence of specimens of *Helminthopsis* sp. It was rather difficult, however, to find the clear mutual relation between the mode of occurrence of trace fossils and the paleo-current directions through the observations at many other outcrops.

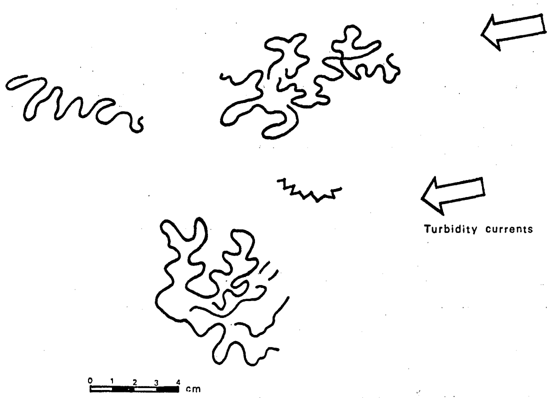

Fig. 6. Direction of turbidite supply and trace fossils (*Helminthopsis*, *Cosmorhaphe* and *Belorhaphe*).

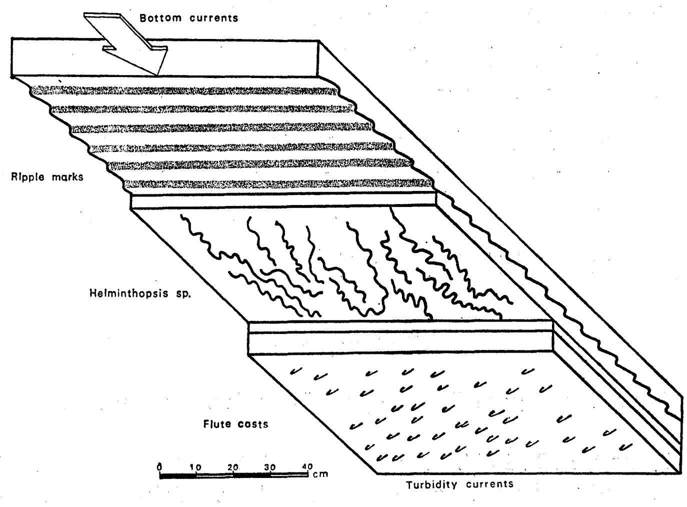

Fig. 7. Direction of bottom currents and trace fossils (*Helminthopsis*).

On the pre-depositional formation of trace fossils, SEILACHER (1961) pointed out that the thicker the sandstone bed, the smaller the number of trace fossil species, and he attributed it to the degree of erosive action of turbidity current, and of consolidation of the underlying mudstone bed. This seems to be an important feature also of the Kayo Formation. As judged from the foregoing BOUMA's model and the thickness of sandstone bed bearing trace fossils, traces could hardly be preserved in the proximal site due to strong erosive action of turbidity current, while in the distal site with rather weak erosive action they could easily be preserved as fossils. This can also be recognized as the change with the lapse of time through the successive facies change of the Kayo Formation (fig. 3). Looking into the four units (K_1-K_4) of the Kayo Formation representing the fining-upward cycles of sedimentation, the following points are recognized.

1) The unit K_1 has no trace fossils.

2) In the units K_2 and K_3, variability of trace fossils increases from the lower to the upper horizons.

3) In the unit K_4, trace fossils attain to the largest number of individuals although they are rather restricted in number of species.

Therefore, it is concluded that the sandstone bed formed under the condition available for the preservation of trace fossils increases in number from the lower to the upper horizons through the Kayo Formation.

Concluding Remarks

Trace fossil assemblage of the Kayo Formation, comprising *Spirorhaphe*, *Spirodesmos*, *Helminthoida*, *Helminthopsis*, *Cosmorhaphe*, *Paleomeandron*, *Belorhaphe*, *Paleodictyon* and a few kinds of feeding burrows, are considered to represent the *Nereites* facies of the SEILACHER's assemblage concept (SEILACHER, 1967). Mode of occurrence of trace fossils seems to be in harmony with the fining-upwards cycles of turbidite sedimentation of the Kayo Formation. Trace fossils increase in their variability and number of individuals from the lower to the upper horizons. Judging from the thicknesses and the internal structures of the overlying sandstone layer, it is concluded that the mode of preservation of pre-depositional sole trails is controlled primarily by the biological environmental condition and secondly by the sedimentological condition. Through the comparison with the traces recorded from modern ocean and geological formations, the ichnofossils described in the present article are judged to represent the lower bathyal to abyssal zone (roughly ranging from 3500 to 5500 meters in depth) as the depth range of their formation.

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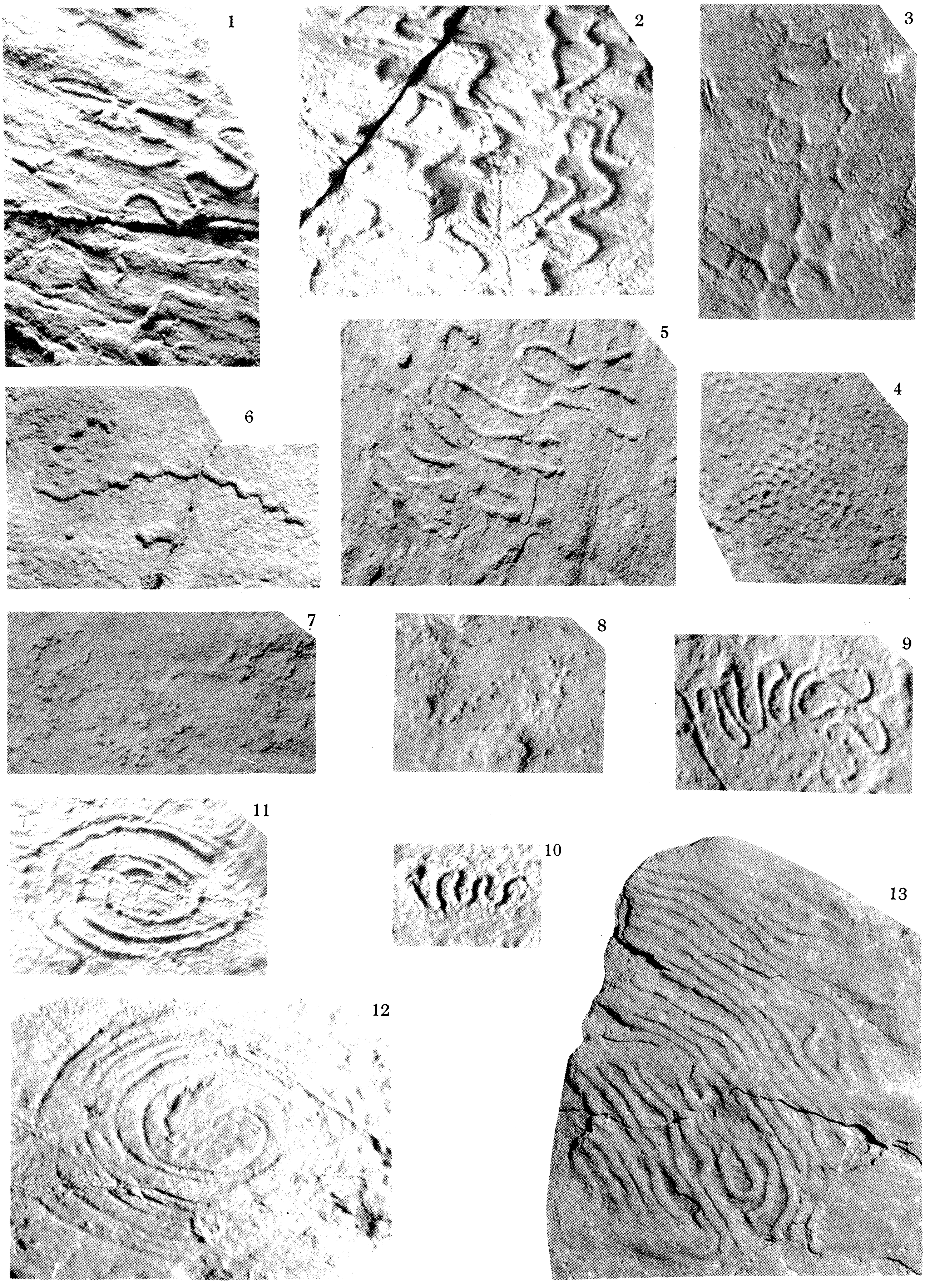
Explanation of Plate 1

(All figures are in natural size unless otherwise stated)

Figs. 1 and 2. *Cosmorhaphe* sp., Loc. no. 21. × 1/2
Fig. 3. *Paleodictyon* sp. a. Loc. no. 4. Plaster model (mold).
Fig. 4. *Paleodictyon* sp. b. Loc. no. 8.
Fig. 5. *Helminthoida* sp. c. Loc. no. 21.
Fig. 6. *Belorhaphe* sp. Loc. no. 2.
Figs. 7 and 8. *Paleomeandron* sp. Loc. no. 21.
Figs. 9 and 10. *Helminthopsis* sp. Loc. no. 25. Plaster model (mold.)
Fig. 11. *Spirodesmos* sp. Loc. no. 25. Plaster model (mold).
Fig. 12. *Spirorhaphe* sp. Loc. no. 21. Plaster model (mold). ×1/2
Fig. 13. *Helminthoida* sp. a. Loc. no. 20. ×1/2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Explanation of Plate 2

(All figures are in a half size)

Figs. 1 and 2. *Helminthoida* sp. b. Loc. no. 19.
Fig. 3. Feeding burrow. Loc. no. 25. Plaster model (mold).
Fig. 4. Bilobed trail with a groove on the ridge. Loc. no. 25. Plaster model (mold).
Fig. 5. *Helminthopsis* sp. Loc. no. 23.

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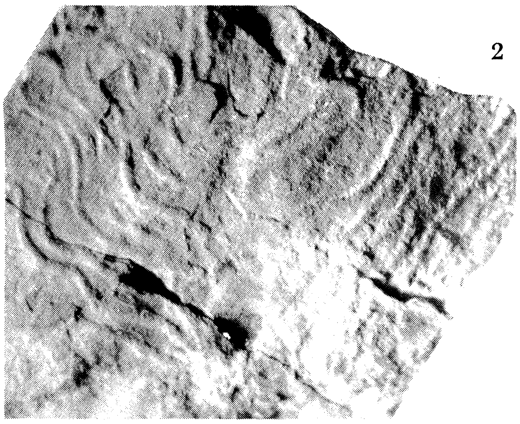

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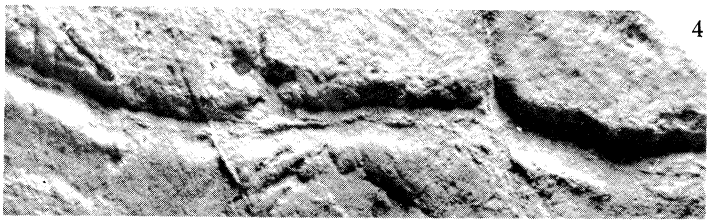

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