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Lower Silurian distal shelf storm-induced turbidites in the Welsh Borders: sediments, tool marks and trace fossils

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SUMMARY: The Upper Llandovery Hughley Shales of Shropshire are interpreted as storm-induced distal shelf turbidites. They comprise a sequence of calcareous sandstones interbedded with purple mudstones. The trace fossils, body fossils, and palaeogeography indicate a deep shelf position for their deposition. The thin sandstone units are interpreted as having been deposited from density current bedload and suspension. Storm surge ebb traction currents, arising from intermittent major offshore storms, are considered to have initiated the density currents. A deepened storm wave base allowed transportation of fine sand in suspension out onto the distal shelf.

Internally, the resultant sands are differentiated from distal (fan) turbidites by multi-directional bedload currents, which are shown most clearly by spectacular tool marks on sandstone bases. The tools are clearly identifiable in many cases as indigenous benthonic organisms such as horn corals, coral colonies, crinoids, brachiopods and trilobites. The sandstone beds were later colonized by burrowers and other track-producing organisms. The trace fossils include *Diplocraterion* (or *Corophioides*), *Palaeophycus*, *Skolithos*, *Chondrites*, *Scolicia*, *Rusophycus*, *Cruziana* and *Diplichnites* (*Cruziana* facies assemblage). A new ichnospecies, *Walcottia devilsdingli* is established for small burrows with regular lateral appendage marks at certain points.

The Lower Silurian Hughley Shales ('Purple Shales' of Whittard 1928) are exposed at several places in the central Welsh Borders region. In their main outcrop, a long narrow strip running NE from the Wrekin to Buildwas, they are 76–107 m thick (Earp & Hains 1971), and consist of mudstones interbedded with thin siltstone and sandstone units.

The Llandovery Series of the area is divided into 3 units: the Kenley Grit, *Pentamerus* Beds and Hughley Shales, of which the latter two are regarded as Upper Llandovery in age (Whittard 1928, 1952; Pocock *et al.* 1938). The Hughley Shales pass conformably into the Buildwas Beds, which are the basal beds of the Wenlock (Bassett *et al.* 1975).

Brachiopods and graptolites collected at Buildwas indicate an assignment of the Hughley Shales to the C_5 Substage of the type Llandovery area, and to the *griestoniensis* Zone, respectively (Cocks & Walton 1968). Fossils from other areas suggest an age range from *turriculatus* to *crenulata* Zones (C_4–C_6), thus latest Llandovery (Telychian) (Cocks & Rickards 1969; Bassett *et al.* 1975).

Current palaeogeographic models (Ziegler *et al.* 1978*b*; Ziegler 1970; Bridges 1975) place the main Hughley Shales outcrop in the middle of the Telychian shelf. The sedimentology, however, indicates the presence of horizons interpreted as turbidites by Cocks & Walton (1968), and we attempt to explain this apparent paradox.

We studied various sections in the main Hughley Shales outcrop, including the Devil's Dingle temporary dam site near Buildwas (SJ 639 052) (Fig. 1), the famous Onny River section near Cheney Longville (SO 4268 8532), and a tributary of Hughley Brook (SO 5622 9762). Several hundred specimens of the 'turbidite-form' beds were collected, and most displayed undersurfaces covered with a spectacular array of well preserved tool marks, and the top surfaces showed a range of finely detailed trace fossils. The sedimentology, tool marks and trace fossils are described, and an interpretation of the origin of the sandy layers in the Hughley Shales is given in terms of shelf storm transport. Figured specimens are deposited in the Hancock Museum, Newcastle-upon-Tyne (H.M.), and other material in the Geology Department, University of Newcastle (N.U.G.D.).

Sedimentology

This section is based on observations and collections made at the Hughley Brook tributary and Devil's Dingle localities. The succession consists of mudstones interbedded with fine calcareous siltstone and sandstone units each 1–20 cm thick.

Mudstone units

The mudstone units are 2–50 cm thick and laterally persistent. They are finely laminated and show occasional siltstone and thin ochrous bands. Colours range from grey-green to chocolate-maroon, and variably developed green 'reduction' spots may be present. The mudstones contain a diverse benthonic fauna dominated by brachiopods and corals.

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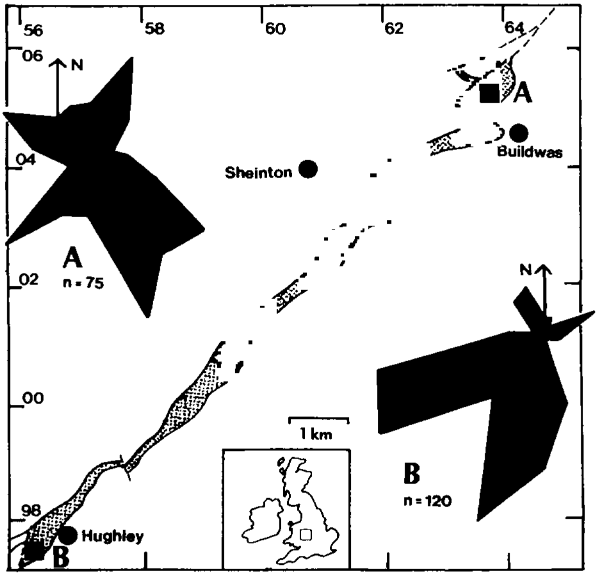


FIG. 1. Northern portion of the main Hughley Shales outcrop in Shropshire (shaded). Palaeocurrent directions, shown by rose diagrams, taken from slabs collected at Devil's Dingle (A) and Hughley Brook tributary (B). Readings taken from unidirectional prod and groove marks (75 readings from A, 120 from B) and grouped in 20° intervals.

Siltstone and sandstone units

The silts and sands vary from 1–20 cm in thickness and are laterally persistent over tens of metres of outcrop, although they pinch and swell gently. They are grey, weathering to buff; their bases are moulds of tool-marked surfaces and their tops contain a diverse assemblage of well-preserved trace fossils.

The silts and sands are mostly well-sorted and grain size is 20–500 μm. The cement is ferroan calcite and the matrix consists of variable proportions of mud and silt-grade material. Clay matrix is minimal, but apparently greater in silt laminae. A small amount of clay material has been introduced post-depositionally through infaunal bioturbation and piping of overlying muds and silts in burrow systems.

The sand sheets are dominated by mm-scale parallel lamination. Laminae alternate and grade between matrix-deficient fine sands and matrix-rich sands and silts. Bioclasts progressively decrease in size and quantity towards the upper laminae of the sand sheets, whereas silt-dominated laminae increase upwards within the beds.

Many sandstone beds show discontinuous coarse shelly layers up to 5 cm thick at the base (Fig. 3*a*), at the top (Fig. 3*b*), and in the middle (Fig. 3*c*). These layers contain a mixed assemblage of clast 'generations' with fragmented, rounded and micritized clasts admixed with undamaged benthos of all ontogenetic stages, and the composition ranges from clast-supported coquinas (rudstones) to matrix (coarse sand)-supported heterogeneous mixtures of fossils and lithic (laminated siltstone) clasts. All coarse layers lack clear fining-upwards grading.

Ripple lamination is also common, and when present, occurs mainly in the middle parts of thicker

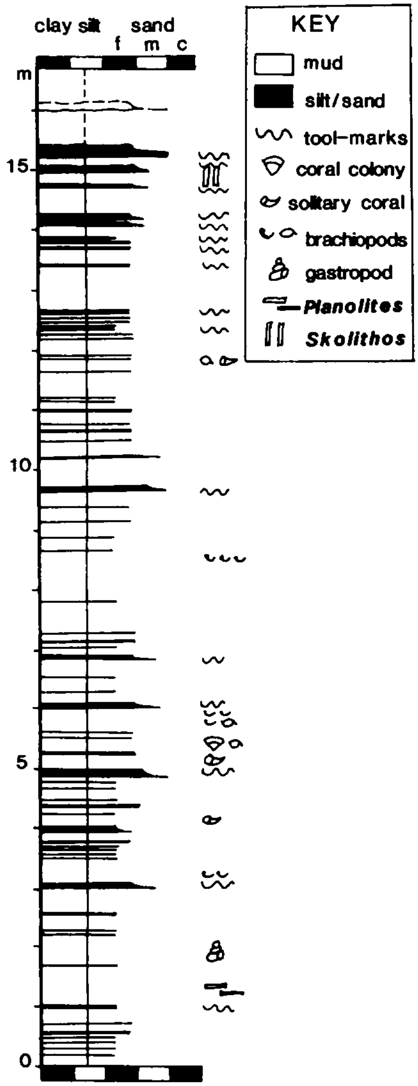


FIG. 2. Sedimentary log of a 16 m section at Devil's Dingle. Fine and coarse units are shown, and relative grain size is indicated by the log to the right. Fossil and trace fossil occurrences are indicated.

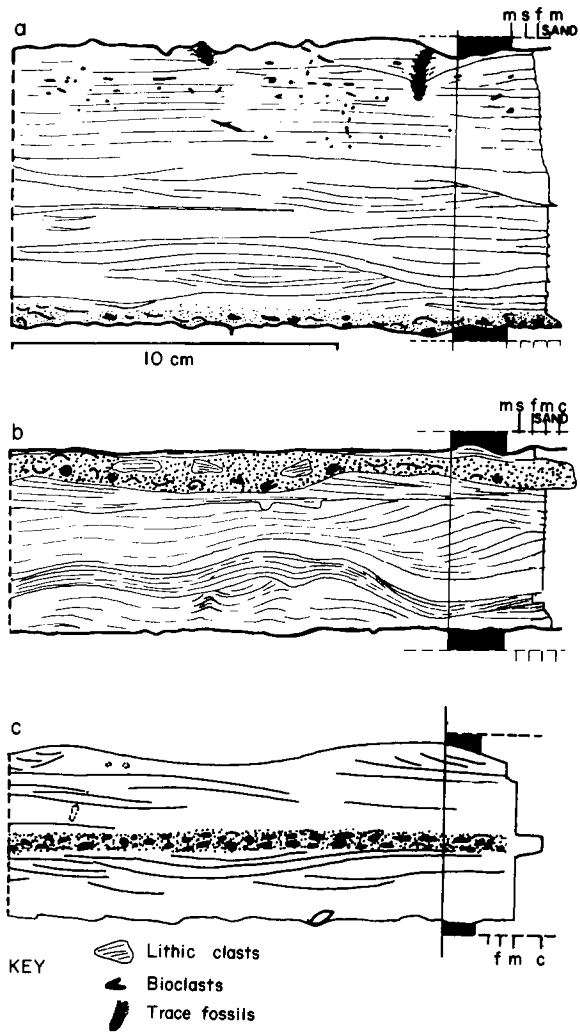


FIG. 3. Cross-sections of sandstone units showing features of lamination, sedimentary structures, fossil lags and trace fossils. Grain size is indicated by the log to the right. Features to note: 3*a*: basal graded unit, internal scours, parallel laminated top, bioturbation; 3*b*: internal scour and coarse clastic lens, type 2 and in-phase climbing ripples, dewatering rupture; 3*c*: central coarse coquina, parallel and ripple lamination, tool included at base, bioturbation.

(>5 cm) sand bodies (Fig. 3*a*). Types 1, 2 and in-phase climbing ripples (Reineck & Singh 1973) dominate in vertically restricted sets (Fig. 3*b*). Climbing ripple sets generally have a complex stratigraphy with internal scour surfaces. Features characteristic of wave activity (e.g. de Raaf *et al.* 1977) are absent.

Other sedimentary structures are present. Shallow depressions (depth ≤5 cm, diameter ≥30 cm) are occasionally seen on the bed base. Upward directed ruptures may occur within ripple-laminated sets and they are truncated by overlying parallel laminated fine sand and silt layers (Fig. 3*b*). Rare erosional furrows (gutter casts) occur along scour surfaces at sand sheet bases. They are up to 12 cm across, with one steeply undercutting bank producing an asymmetrical cross section. Smaller tool marks trend at an angle to the axis of these furrows.

Palaeocurrents

Current directions were measured from unidirectional groove marks and prod marks on two slabs, each about 1 m square, from the Hughley Brook tributary and from Devil's Dingle (Fig. 1). The Hughley Brook slab (Figs 1B, 4) shows two major current directions, one directed SSW (from 020°), and the other WSW (from 070°). Neither direction occurs first everywhere, nor is either associated with a particular suite of tool marks, but the long axes of some shallow furrows that parallel the SSW current direction may be discerned. The Devil's Dingle slab does not indicate a single dominant direction (Fig. 1A), and the tool marks are more crowded and confused than in the first specimen. Transport directions estimated from ripple lamination are in approximate agreement with underlying tool-marked surfaces.

Bridges (1975) interpreted the *Pentamerus* Beds as near-shoreface deposits and postulated a Telychian coastline of the Midland Block 150 km to the E and running roughly NNE–SSW. The 'shelf' margin probably lay some tens of km to the W. Thus the Hughley Shales current directions are shore-parallel to offshore. These compare with the NW offshore directions obtained by Cocks & Walton (1968) from random samples at Devil's Dingle.

Fauna

The indigenous body fossils of the Hughley Shales are reviewed briefly because of their palaeoenvironmental importance, and because they were common as tools.

The rugose corals include the small *Cantrillia* and *Calostylis*, and the larger *Streptelasma*, *Cystiphyllum* and *Phaulactis* (Smith 1930). Tabulates include *Halysites*, *Aulopora*, *Favosites*, *Heliolites*, *Thecia* and *Propora*. Trilobites include species of *Cyphoproetus* (*Warburgella*), *Leonaspis*, *Eophacops*, *Stenopareia*, *Lichas*, *Encrinurus*, *Phacops*, *Dalmanites* and *Cheirurus* (Whittard 1938; Cocks & Walton 1968). Bassett *et al.* (1975, p. 13) listed the following brachiopods from the top 10 m of the Hughley shales, in decreasing order of abundance: *Eoplectodonta*, *Glassia*, *Visbyella*, *Atrypa*, *Aegiria*, *Mesopholidostrophia*, *Leptaena*, *Skenidioides*, *Craniops*, *Resserella*, *Dicoelosia*, *Amphistrophia*, *Eocoelia*, *Dictyonella*, *Coolinia*, *Cyphomerioidea*, *Clorinda*, *Pentlandia*, *Cyrtia*, and *Eospirifer*. Cocks & Walton (1968) mentioned these, and *Costricklandia*, from Devil's Dingle. Graptolites from Devil's Dingle are: *Monograptus priodon*, *M. nudus* and *Acanthograptus* sp. (Cocks & Walton 1968). Graptolites occurring elsewhere in the Hughley Shales include: *Dictyonema* sp., *Monograptus turriculatus*, *M. marri*, *M. spiralis*, *M. griestoniensis*, '*Spirograptus*', and '*Retiolites*' (Cocks & Rickards 1969). Bassett *et al.* (1975) quoted *Monograptus parapriodon*, *M. priodon*, and *M. discus*. Other fossils include ostracods, crinoids, a carpoid, a cystid (Cocks & Walton 1968), bryozoans, bivalves, gastropods, orthoceratids and tentaculitids.

Cocks & Walton (1968) and Cocks & Rickards (1969) ascribed the Hughley Shales to the *Clorinda* community of Ziegler (1965) and Ziegler *et al.* (1968*a*), with a *Clorinda*/*Stricklandia* community mix at the top. Cocks & Rickards (1969) noted an impoverished 'Marginal *Clorinda*' community at the top of the Hughley Shales elsewhere. The *Clorinda* community is regarded as the deepest (most distal) shelf brachiopod facies of the Llandovery, and the *Stricklandia* community indicates slightly shallower conditions (Cocks & Walton 1968).

Tool marks

Dżułyński & Walton (1965, p. 38) classified tool marks as follows:

Continuous marks:	Groove marks
	Chevron marks
Discontinuous marks:	Prod marks
	Bounce marks
	Brush marks
	Skip and roll marks
Rilled tool marks	

Tool marks on the bases of the Hughley sandstones are chiefly moulds of groove marks, prod marks and bounce marks (Fig. 4). In addition, there are forms which we term *pluck marks* (produced by the plucking of a fossil partially embedded in the substrate), *in-out groove marks* (combined entrance prod mark and exit groove mark), and *prod-rotation marks* (light prod mark with rotation of tool before lift-off).

In our material, we found no evidence of chevron marks, brush marks (low angle prod marks with mound of sediment downstream of deepest part), skip and roll marks, or rilled tool marks. Skip and roll marks are common in turbidites (Dżułyński & Walton

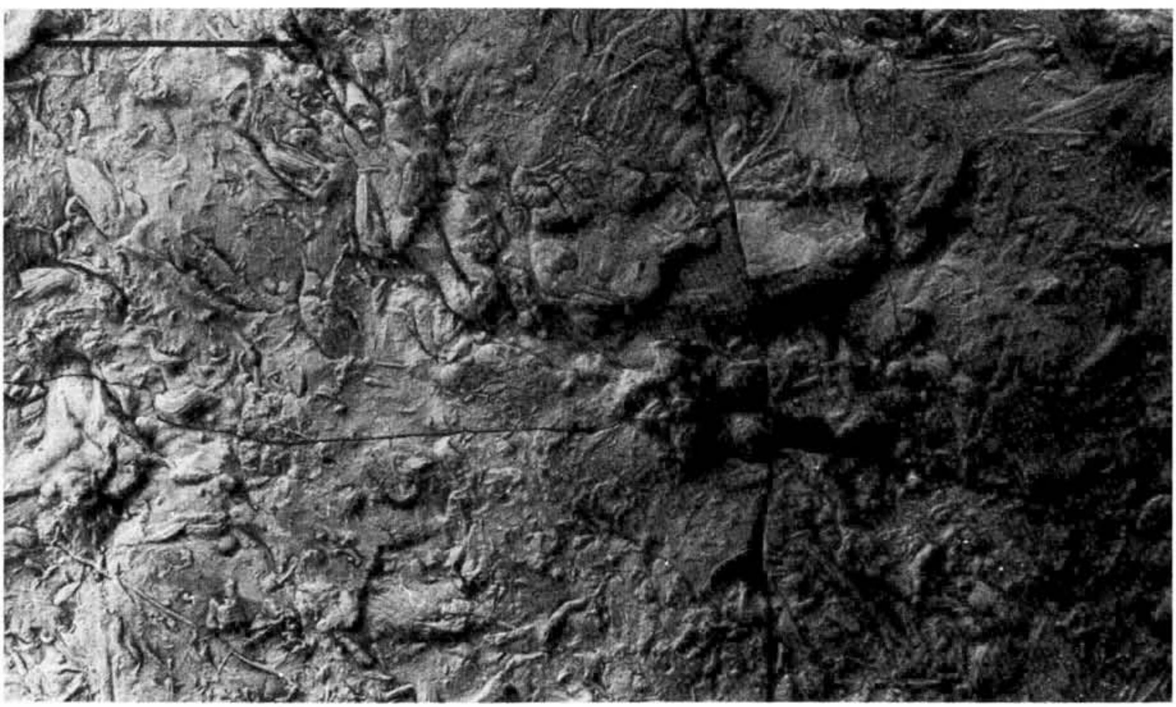


FIG. 4. Tool-marked under surface of a sandstone unit from Hughley Brook tributary (palaeocurrent slab B). Scale bar represents 5 cm.

1965; Kelling & Whitaker 1970; Bates 1974; Trewin 1979), where they appear to be associated with low energy density flows.

Tools recorded in place within tool marks include wood, fish bones, lithoclasts and shells (Dżułyński & Walton 1965, p. 111). In the Hughley material brachiopods, corals and crinoid ossicles are associated with tool marks (Fig. 3*c*). Other available tools here are trilobites, bryozoans and lithoclasts.

The objects producing the tool marks can be identified with reasonable certainty in some cases, on the basis of details of tool mark shape and size when included fossils are absent.

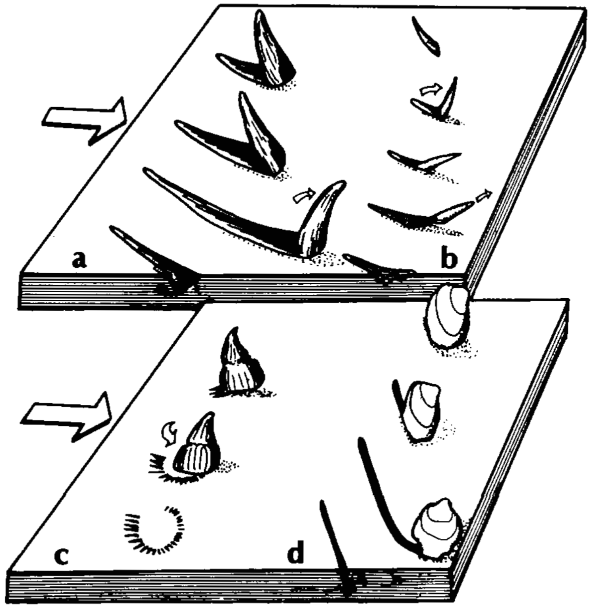


FIG. 5. Proposed modes of formation of various Hughley Shales tool marks. Current direction indicated. *a*, horn coral groove mark; *b*, horn coral in–out groove mark; *c*, horn coral prod-rotation mark; *d*, brachiopod edge groove mark.

Solitary horn corals

(*a*) *Groove mark.* Among the commonest identifiable tool marks, horn coral groove marks range in width from 2 to 10 mm, averaging 6–8 mm. They may be shallow to deep, and commonly show regular longitudinal striations produced by the septal ridges of the corals. The deepest part points down-current where the coral has come to a stop and lifted off the substrate (Figs 5*a*, 6*a*,*b*).

(*b*) *In-out groove mark.* In some cases, the horn coral enters the substrate, digs in, flips over and pulls out, leaving a deep entry prod and shorter exit trail (Fig. 5*b*). The best examples (Fig. 6*c*,*d*) are 4–5 mm wide, up to 3 mm deep, and show definite alignment.

(*c*) *Pluck mark.* Some horn coral grooves show a pointed element that stuck deep into the mudstone (Fig. 6*e*). These are probably casts of horn corals which have been plucked from the substrate.

(*d*) *Calice prod mark.* Several circular prod marks were clearly formed by horn corals (Fig. 6*f*,*g*). Some of them show the impression of a 3 mm wide rim with 16 or more septa, and a central depression, 6 mm across. This corresponds to the rugose corals *Phaulactis* or *Streptelasma*. The specimen figured in Fig. 6*h* could be a horn coral prod mark or a brachiopod prod mark.

(*e*) *Septa prod mark.* One specimen (Fig. 6*i*) shows impressions of 7 septa where a medium-sized horn coral has touched down lightly.

(*f*) *Calice prod-rotation mark.* Two examples (Fig. 6*j*,*k*) show distorted subcircular impressions, 11 and 8 mm across, rimmed by septal impressions. They appear to have been caused by a horn coral touching the substrate lightly, and rotating before lifting off (Fig. 5*c*).

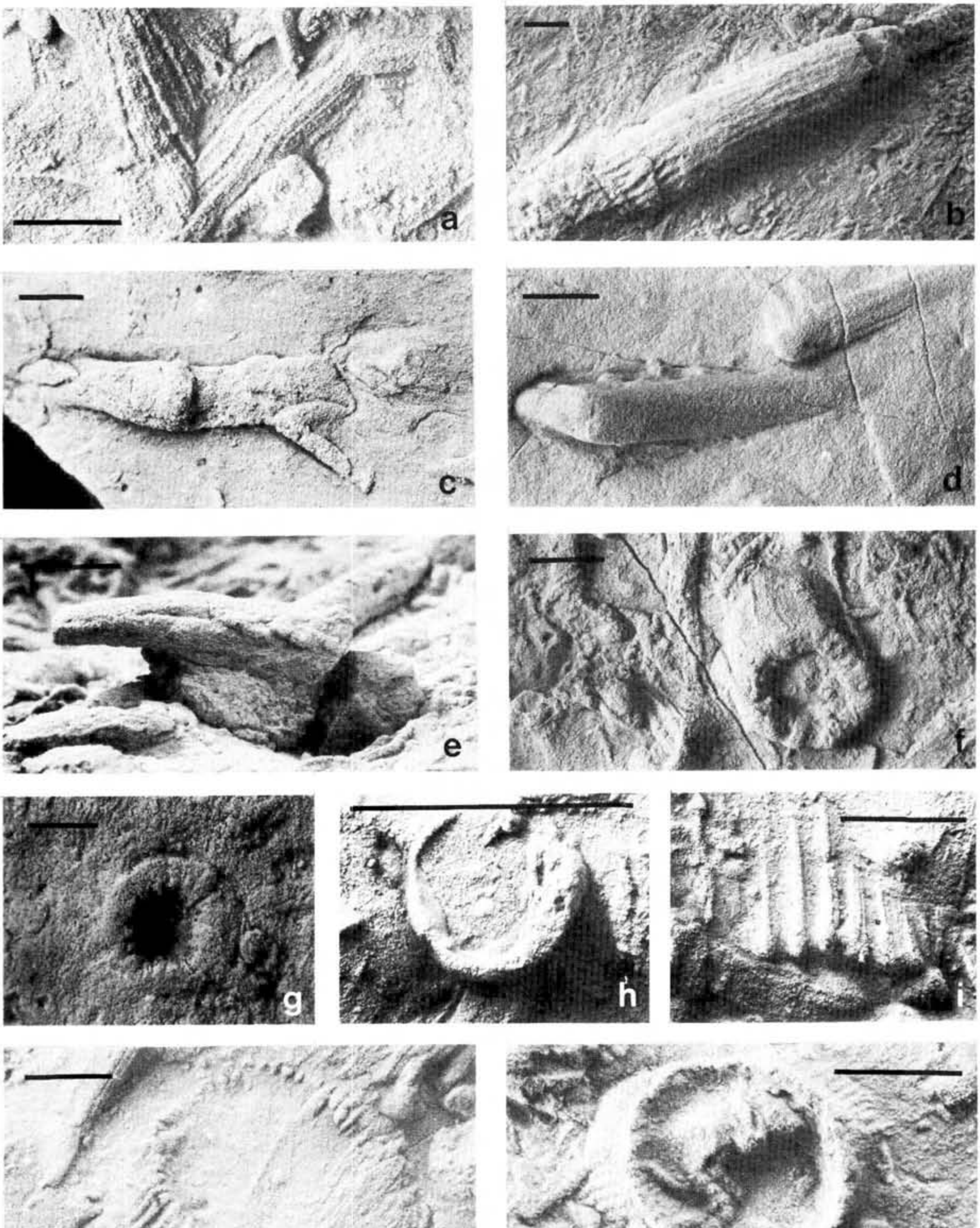
Tabulate corals

(*a*) *Favositid bounce mark.* Several specimens show light reticulate patterns of polygons. There are two sizes (Fig. 7*a*,*b*); small, with polygons 1–1.5 mm across, and large, with polygons 2–4 mm across. These match in size and shape the tops of favositid calices, and it is clear that the tool was a small colony bouncing lightly along the bottom.

(*b*) *Tabulate colony groove mark.* Large groove marks, 5–6 mm broad (Fig. 7*c*) were probably formed by heliolitid or favositid colonies which were the only fossils of the appropriate size and shape.

(*c*) *Tabulate colony prod.* Some 6–8 cm long prod marks correspond to the outline of a cerioid tabulate colony, and show impressions of smudged epithecal rugae.

(*d*) Halysites *chain prod mark.* There is little doubt about the origin of a beautiful prod mark made by a *Halysites* chain consisting of 7 corallites (Fig. 7*d*), and another consisting of 4 corallites (Fig. 7*e*). The corallites are 2.5×1.7 mm in size. A section taken through the second specimen revealed no traces of a fossil coral within, and this confirms that it is a prod mark.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(*e*) Aulopora *groove and prod marks.* An impression consisting of five 4 mm sausage-shaped elements (Fig. 7*f*) may be the mark of a small *Aulopora* chain. In another specimen, an *Aulopora* is preserved within a groove mark (Fig. 7*g*), indicating that it is possibly the tool. Elsewhere, another *Aulopora* chain lies at the end of a narrow groove mark that it may have produced (Fig. 7*h*). Finally, 2–3 mm circular prod marks match the calice form and size of *Aulopora* (Fig. 7*i*).

Crinoids

One of the commonest tool mark forms is a blade-like strip, 1–3 mm wide, very shallow, but clearly distinguishable from the substrate. Some of these are associated with crinoid ossicles, or groups of ossicles (Fig. 7*j*,*k*), and it is likely that these are the originators.

Brachiopods

(*a*) *Groove marks.* Several specimens (e.g. Fig. 8*a*) show brachiopods (cf. *Skenidioides*, cf. *Atrypa*) at the ends of the grooves they formed.

(*b*) *Prod marks.* A subrectangular prod, 7 mm across, shows the form of a brachiopod shell that has impinged upon the substrate (Fig. 8*b*).

(*c*) *Edge groove marks.* Deep groove marks, apparently produced by large flat brachiopods being dragged through the sediment on edge, are relatively common (Fig. 8*c*,*d*). The second example has a piece of cf. *Costistricklandia* shell in place in the groove. They appear to cross-cut the general current sense, and change direction frequently, their progress being governed by the current and sediment resistance to the high impedance of a broad flat shell (Fig. 5*d*). This is suggested also by the evidence of jerky progression when the tool mark is examined in side view (Fig. 8*e*).

The grooves are 1–3 mm across and 1–7 mm deep. Small forms (Fig. 8*f*) may have been formed by small brachiopods or stick bryozoans. One example (Fig. 8*g*) may be more a brachiopod edge prod than a groove; it is up to 7 mm broad and 4 mm deep. Dżułyński & Walton (1965, p. 89) showed that tools readily twist while forming a groove mark, and Osgood (1970, pp. 392–3, pl. 80, fig. 7) figured tool marks made 'by twisting brachiopod shell fragments'.

Trilobites

The most spectacular tool marks are those produced by trilobites. The specimen illustrated in Fig. 8*h*,*i* shows a deep impression of the 4.5 mm wide anterior and lateral margins of the cephalon, which measures 11.4 mm in greatest transverse width. The glabella is clearly visible, and impressions of the first 3 or 4 axial segments follow behind.

The second specimen (Fig. 8*j*) shows a beautiful glabella with the glabellar furrows, the occipital ring, and the first 5 axial segments. Part of the anterior border and the palpebral lobe on the right hand side are also preserved as impressions. This tool mark corresponds to a calymenid.

These impressions were produced by trilobite carcasses bouncing upside down on the sediment. They are not internal moulds of trilobite carapaces, and there is no trace of cuticle present.

Trace fossils

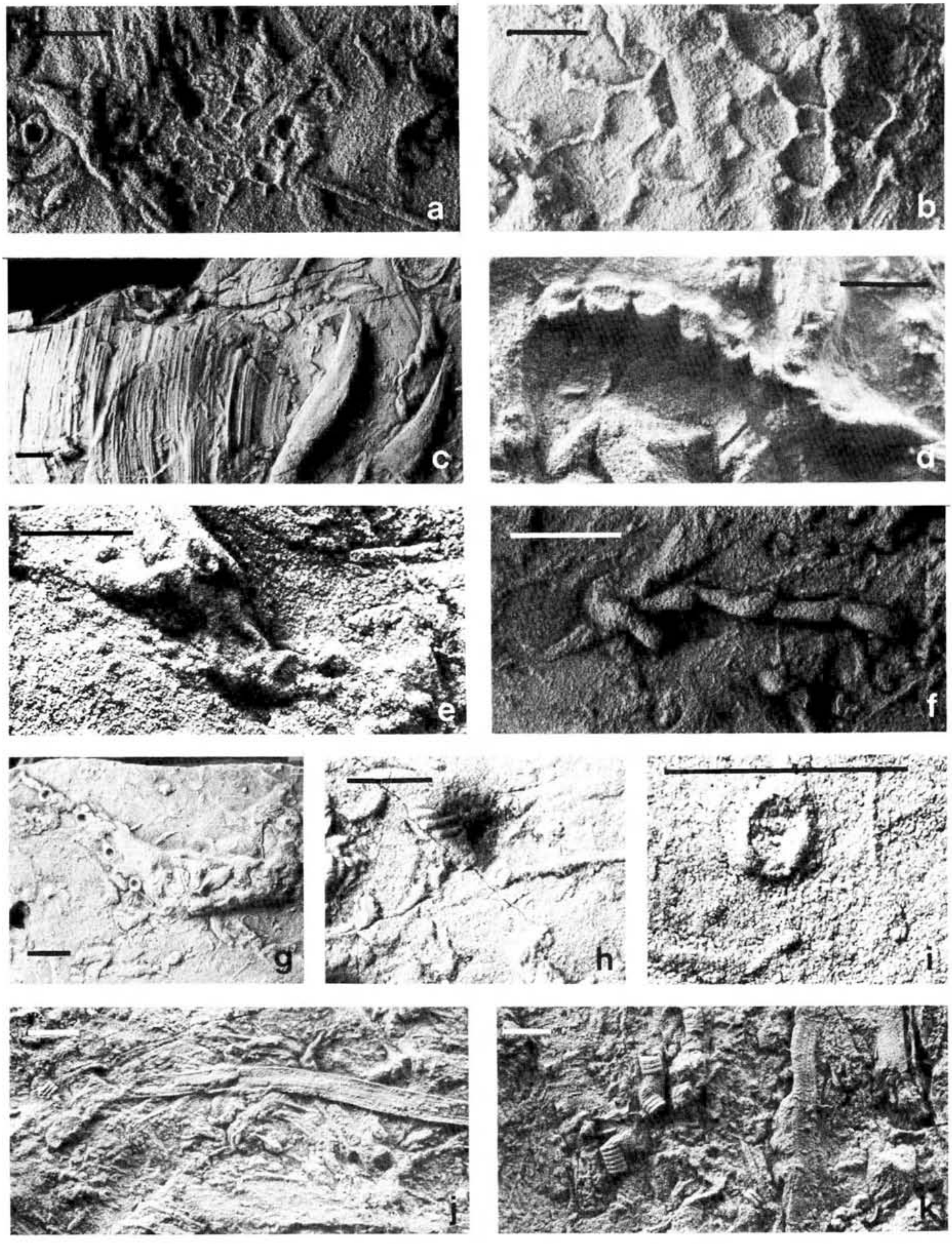
A range of trace fossils was observed in the sandstone units. These indicate a diverse fauna living in the top parts of the sand and superincumbent mud [*Diplocraterion* (or *Corophioides*), *Skolithos*, *Walcottia*], feeding within the sand (*Chondrites*, *Palaeophycus*), and on the lower tool-marked surface (*Scolicia*). Rare trilobite traces (*Rusophycus*, *Cruziana*, *Diplichnites*) occur on top of the sandstone units and on the tool-marked surface. Small burrows, possibly produced by trilobites, occur within the sand. The distribution of trace fossils in the different Hughley Shales sediments is indicated in Fig. 9.

Domichnia

Ichnogenus *Diplocraterion* Torell 1870 (or *Corophioides* Smith 1893)

FIG. 6. Tool mark moulds on bases of sandstone units of the Hughley Shales, produced by solitary horn corals. Figs *a*–*g* from Devil's Dingle, Figs *h*–*k* from Hughley Brook tributary. Scale bar represents 5 mm.

a, *b*, Horn coral groove marks, HM G159.31, HM G159.32; *c*, *d*, Horn coral in-out groove mark, HM G159.33, HM G159.34; *e*, Horn coral pluck mark, HM G159.35; *f*, Horn coral prod/groove mark, HM G159.36; *g*, Horn coral prod mark, HM G159.37; *h*, Horn coral, or brachiopod, prod mark, NUGD B; *i*, Horn coral septa prod mark, NUGD B; *j*, *k*, Horn coral calice prod-rotation mark, NUGD B.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The tops of most sandstone units are covered with shallow non-aligned U-shaped impressions, which range from shallow gutters to circular burrows, just covered on top (Fig. 10*a*). The impressions are 6–9 mm thick and up to 6 cm wide, using the topographic terminology of Knox (1973). These are the bases of large U-shaped burrows that extended down from the mud above. Unfortunately, a complete burrow could not be collected because of the friable nature of the mudstone.

In general appearance, these traces closely resemble U-shaped burrow bases from the Lower Triassic of Germany described by Blanckenhorn (1916) as *Arenicoloides luniformis* (refigured by Häntzschel 1975, fig. 31, 5*c*), and some Ordovician material from Ohio figured by Osgood (1970, pp. 320–1, pl. 61, fig. 5, pl. 62, fig. 2). *Arenicoloides* has been synonymized with *Diplocraterion* by Knox (1973), but Osgood (1970, pp. 317, 320–1) and Häntzschel (1975, p. W53) placed it in *Corophioides*. The Hughley specimens are not *Arenicolites* since there is evidence of spreite in many (Fig. 10*b*). The distinction between *Corophioides* and *Diplocraterion* is that succeeding vertical burrows coincide in the latter, but tend to migrate laterally in the former (Knox 1973). Osgood (1970, p. 317) distinguished *Diplocraterion* and *Corophioides* by the presence of funnels in the former. There is no evidence in the present material to identify which generic name should be used.

The inhabitant of the burrow was a suspension-feeding animal, 5–10 mm in diameter, and one which did not like to burrow into sand.

Environmental interpretation. Both *Corophioides* and *Diplocraterion* appear to be characteristic of shallow water, commonly littoral or estuarine (*Skolithos* facies of Seilacher) or slightly deeper (*Cruziana* facies). The spreiten develop in response to erosion and deposition of sediment.

Ichnogenus *Skolithos* Haldemann 1840

Shallow vertical unbranched burrows, 2–3 mm in diameter, are seen on the top of some sandstone units. They show a 'lip' at the top (Fig. 10c) and taper downwards to a maximum depth of 2 cm, generally not passing right down through the sandstone unit. These burrows were presumably occupied by suspension-feeding animals.

Environmental interpretation. '*Skolithos* is indicative of shallow water environments' (Alpert 1975) and gives its name to the littoral *Skolithos* zone of Seilacher.

Fodinichnia

Ichnogenus *Scolicia* De Quatrefegas 1849

A single specimen (Fig. 10*d*) shows a short stretch of a burrow on a tool-marked surface. It has a deep central portion, 1.0 mm wide, and transversely striated margins, giving a total width of 2.8 mm. It may have been formed just after the first layers of sand had been deposited. Although very small, this appears to belong to the *Scolicia* group and resembles '*Subphyllochorda*' as figured by Häntzschel (1975, fig. 66, 2). *Scolicia* includes gastropod and bivalve trails, but some specimens, like ours, are burrows, and were probably formed beneath a thin sediment cover, and they may have had a different origin.

Environmental interpretation. Häntzschel (1975, p. W106) stated that trace fossils of the *Scolicia* type are known from mid-shelf *Cruziana* and deep-water *Nereites* facies.

Ichnogenus *Chondrites* von Sternberg 1833

One of the commonest traces on the tops of sandstone units, and within them, is a small *Chondrites* (Fig. 10*e*). The burrows are circular, 0.5–1.8 mm (average 1.0 mm) in diameter, and bifurcate regularly, forming branches 0.5–4.0 cm long. The systems are preserved as concave epireliefs and generally remain at one level in the sediment, but terminal branches may show level changes. Fig. 10*f* shows another branching form, rather smaller than the others, with 0.2 mm wide branches in trifurcating units about a central axis. These two forms resemble the *Chondrites* type-B and *Chondrites gracilis* (Hall 1852) specimens figured from the Upper Ordovician of Ohio and Silurian of New York respectively by Osgood (1970, pl. 64, fig. 7; pl. 69, fig. 8).

Environmental interpretation. Chondrites is known from all environments from shallow water to deep sea (Häntzschel 1975, pp. W49–52).

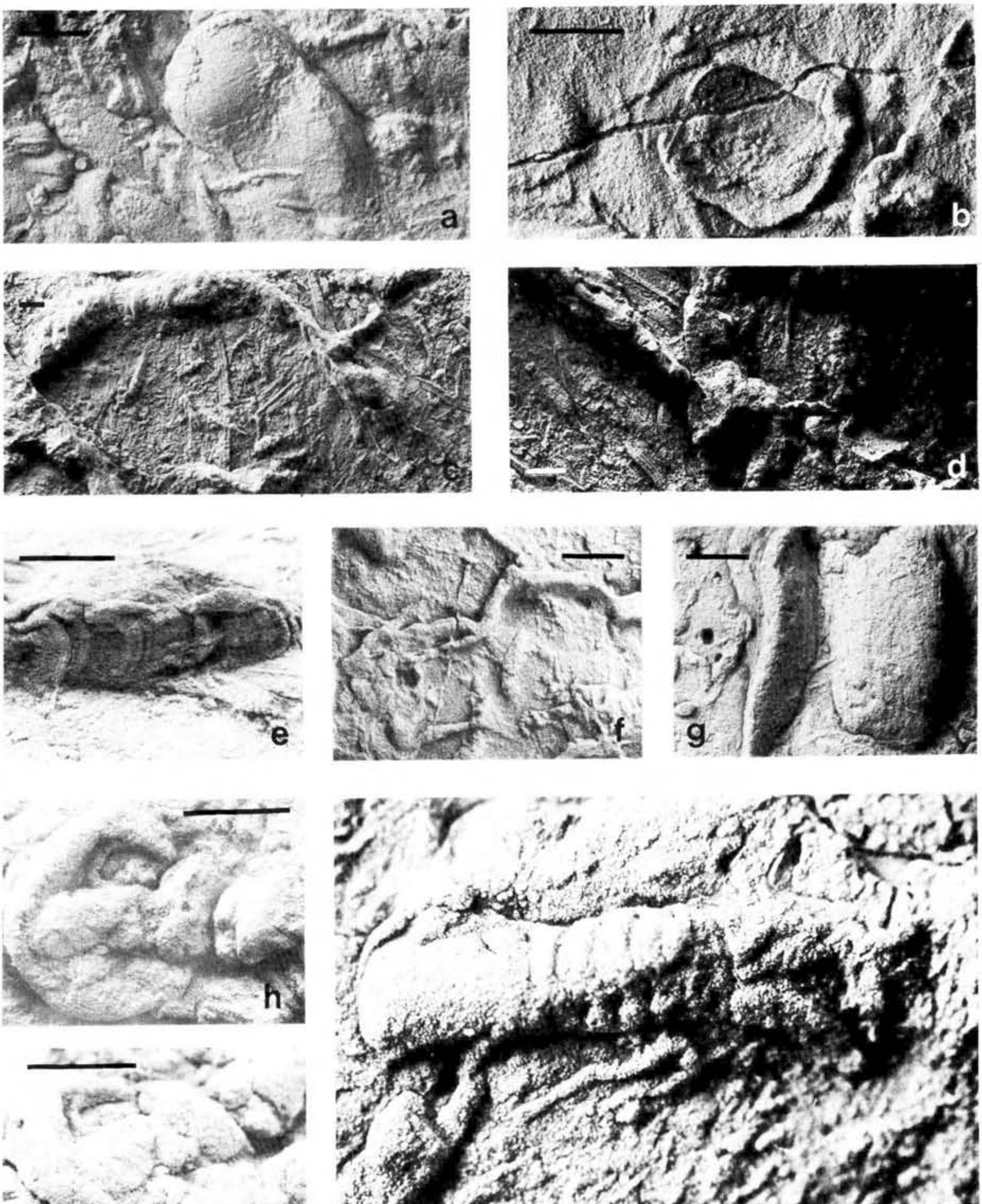
Fodinichnia/Repichnia

Ichnogenus *Palaeophycus* Hall 1847

Horizontal and subhorizontal burrows of various kinds occur upon and within the sandstone units. A

FIG. 7. Tool mark moulds on bases of sandstone units of the Hughley Shales, produced by coral colonies and crinoids. *d* from Hughley Brook tributary, others from Devil's Dingle. Scale bar represents 5 mm.

a, *b*, Favositid bounce mark, HM G159.38; *c*, Tabulate colony groove mark, HM G159.39; *d*, *e*, *Halysites* chain prod mark, NUGD B, HM G159.31; *f*, *Aulopora* colony bounce mark, HM G159.38; g, *Aulopora* colony in groove mark, HM G159.39; *h*, *Aulopora* colony at end of fine groove mark, HM G159.39; *i*, *Aulopora* calice prod mark, HM G159.40; *j*, *k*, Crinoid ossicles and groove mark, HM G159.41.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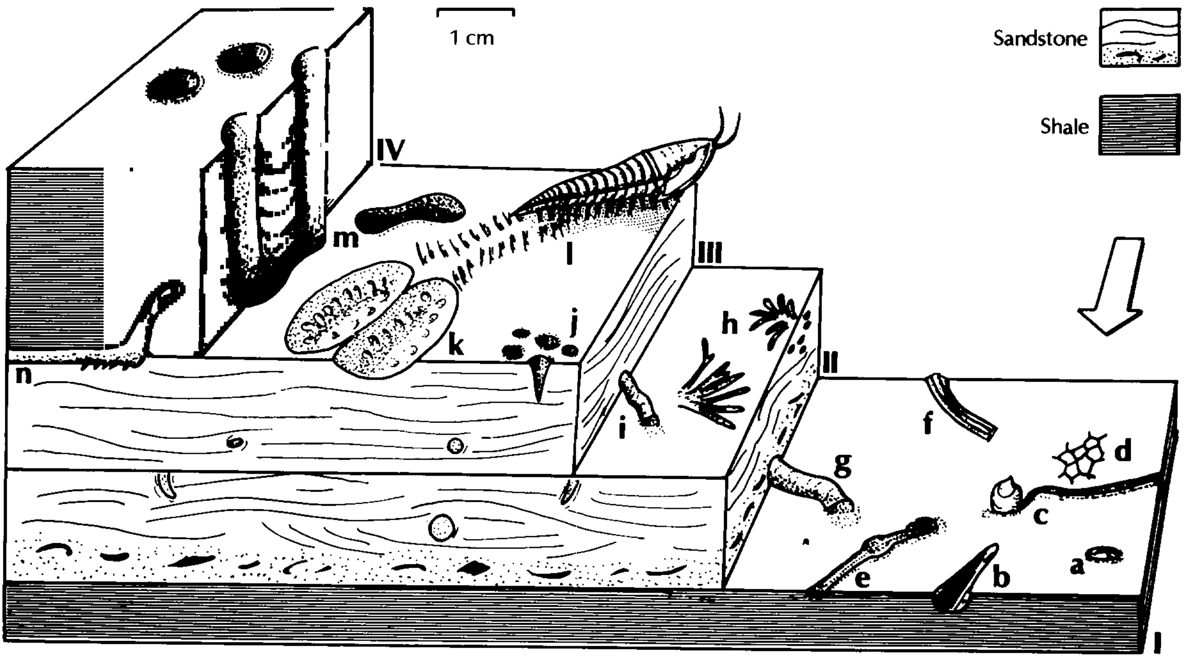


FIG. 9. Trace fossils of the Hughley Shales. Lithofacies associations I–IV. I: Tool-marked mudstone bed; *a*, horn coral calice prod mark; *b*, horn coral groove mark; *c*, brachiopod edge groove mark; *d*, favositid bounce mark; *e*, *Cruziana* (*Isopodichnus*) *problematica* and suggested producer; *f*, *Scolicia*; *g Palaeophycus*. II: Lower part of sandstone unit; *h*, *Chondrites*; *i*, *Palaeophycus*. III: Upper part of sandstone unit; *j*, *Skolithos*; *k*, *Rusophycus*; *l*, *Diplichnites* and proposed producer. III and IV: Overlying shale unit; *m*, *Diplocraterion* (or *Corophioides*); *n*, *Walcottia devilsdingli* ichnosp. nov.

6 mm wide gutter with a lip on either side (Fig. 10*g*) represents the mould of a horizontal burrow. A 4 mm burrow on a tool marked surface shows a collapsed portion where the cross-section is that of an ellipse depressed centrally on top (Fig. 10*h*). Another collapsed burrow (Fig. 10*i*) is rather broader (9 mm), and shows regular transverse ribs which appear to be impressions produced by peristaltic movement of the trace-producing animal rather than simple backfill. However, other specimens (Fig. 10*j*) show oblique backfill laminae where the burrow has been broken.

Horizontal, cylindrical, stuffed burrows may be called *Planolites* or *Palaeophycus*. The distinguishing features depend largely on their proposed modes of origin; *Planolites* is produced by an animal ingesting sediment and passing it through its body, while *Palaeophycus* is a backfilled burrow. The burrow fill in the latter should be the same as the surrounding matrix; there may be backfill structures, and branching may occur (Alpert 1975; Benton & Trewin 1978). The Hughley material shows all these features and it is ascribed to *Palaeophycus*.

Environmental interpretation. Stuffed burrows of the *Palaeophycus* group occur in all environments.

Ichnogenus *Palaeophycus* with body impressions (?)

Two specimens of horizontal burrows show structures that are here interpreted as impressions of parts of the animal's body. The specimen in Fig. 11*a* is an aborted 5 mm broad side branch of a large burrow (shown in Fig. 10*i*) on the base of a sandstone unit. The side branch shows transverse annulation and a paired circular impression at the end. These latter

FIG. 8. Tool mark moulds on bases of sandstone units of the Hughley Shales produced by brachiopods and trilobites. *a* and *b* from Hughley Brook tributary, *c*–*l* from Devil's Dingle. Scale bar represents 5 mm.

a, cf. *Atrypa* in groove mark, NUGD B; *b*, Brachiopod prod mark, HM G159.39; *c*, Brachiopod edge groove mark, HM G159.41; *d*, Brachiopod shell fragments in edge groove mark, HM G159.41; *e*, Detail of side of brachiopod edge groove mark, HM G159.41; *f*, Small brachiopod edge, or stick bryozoan, groove mark, HM G159.42; *g*, Brachiopod edge prod or groove mark, HM G159.43; *h*, Trilobite prod mark, view from above, HM G159.44; *i*, Trilobite prod mark, oblique front view, HM G159.44; *j*, Trilobite prod mark, HM G159.32.

marks could represent the head or tail end of the animal as it backed out of the side branch, or changed level in the sediment.

A more remarkable specimen (Fig. 11*b*,*c*) is an isolated 2 cm stretch of a circular burrow, 2.6 mm in horizontal diameter. It shows a series of regular plate-like impressions, each about 0.3 mm long. They are apparently arranged in longitudinal rows, and at least two rows can be distinguished on one side. There is no sign of smudging of the impressions by movement. In general form, this impression resembles polychaete annelids of the superfamily Aphroditoidea, which have paired rows of overlapping circular or elliptical dorsal scales (Pettibone 1953).

Ichnogenus *Walcottia* Miller and Dyer 1878

Some specimens from the Hughley Shales appear to represent a new species of the obscure and little-known ichnogenus *Walcottia*.

Walcottia was established for '... long, tapering, rugose, flexuous bodies, worm-like in form ... [which] come to a point at one end and are enlarged at the other, or present the appearance of suddenly bending down and entering the rock' (Miller & Dyer 1878, p. 16). The type specimens of the type species, *W. rugosa* from the Upper Ordovician of Cincinnati, were refigured by Osgood 1970 (pl. 67, fig. 6; pl. 69, fig. 5). The first specimen shows a 1.4 cm long, 3 mm wide convex hyporelief with 6 paired laterally directed lobes, and it terminates in a structureless ovoid mass measuring 6×4 mm. The second specimen is similar, but 4 cm long and the lobes do not continue right to the end of the specimen. The lobes are deeply incised, meet in the middle to form chevron shapes, and there are about 10 per cm. The other described species of *Walcottia*, *W. cookana* Miller & Dyer 1878 and *W. sulcata* James 1881, are poorly known and are effectively undefined (Osgood 1970).

Walcottia is relegated to 'unrecognized and unrecognizable genera' in the *Treatise* (Häntzschel 1975, p. W187). However, the species *W. rugosa* is well figured and described by Miller & Dyer (1878) and Osgood (1970), and it should be reinstated as a valid trace fossil genus name.

The 'ladder trails' figured by Hakes (1977, pl. 1*a* (p. 217), p. 222) from late Pennsylvanian marginal marine sandstones of Kansas are very like *Walcottia*. They are up to 3 cm long with lateral ridges, 0.6–0.9 mm apart. The trace is 1.8–3.1 mm wide and may terminate in an 'almond-shaped convex structure', 4×7–8 mm in size. The ichnogenus *Sustergichnus* Chamberlain (1971, p. 231, pl. 31, figs 8, 11) from the Carboniferous flysch of the Ouachita Mountains consists of 40 mm trails, 1–2.5 mm wide, striated in a chevron pattern and occurring at the sand/mud interface. Although no mention is made of terminations, this ichnogenus is clearly similar to *Walcottia*. The material of '*Crossopodia* sp.' described by Hattin & Frey (1969) from the Upper Cretaceous of Kansas, Oklahoma and Iowa may also belong to *Walcottia*. Specimens are generally short and may terminate in a 'bulbous structure'.

The Hughley Shales material differs from *W. rugosa* and the Carboniferous and Cretaceous forms in the less regular, and less deeply incised nature of the lateral lobes, and the presence of a 'halo' of lobes behind the ovoid termination. Thus, it is described as a new ichnospecies here.

Walcottia devilsdingli ichnosp. nov. Figs 11*d*–*g*, 12.

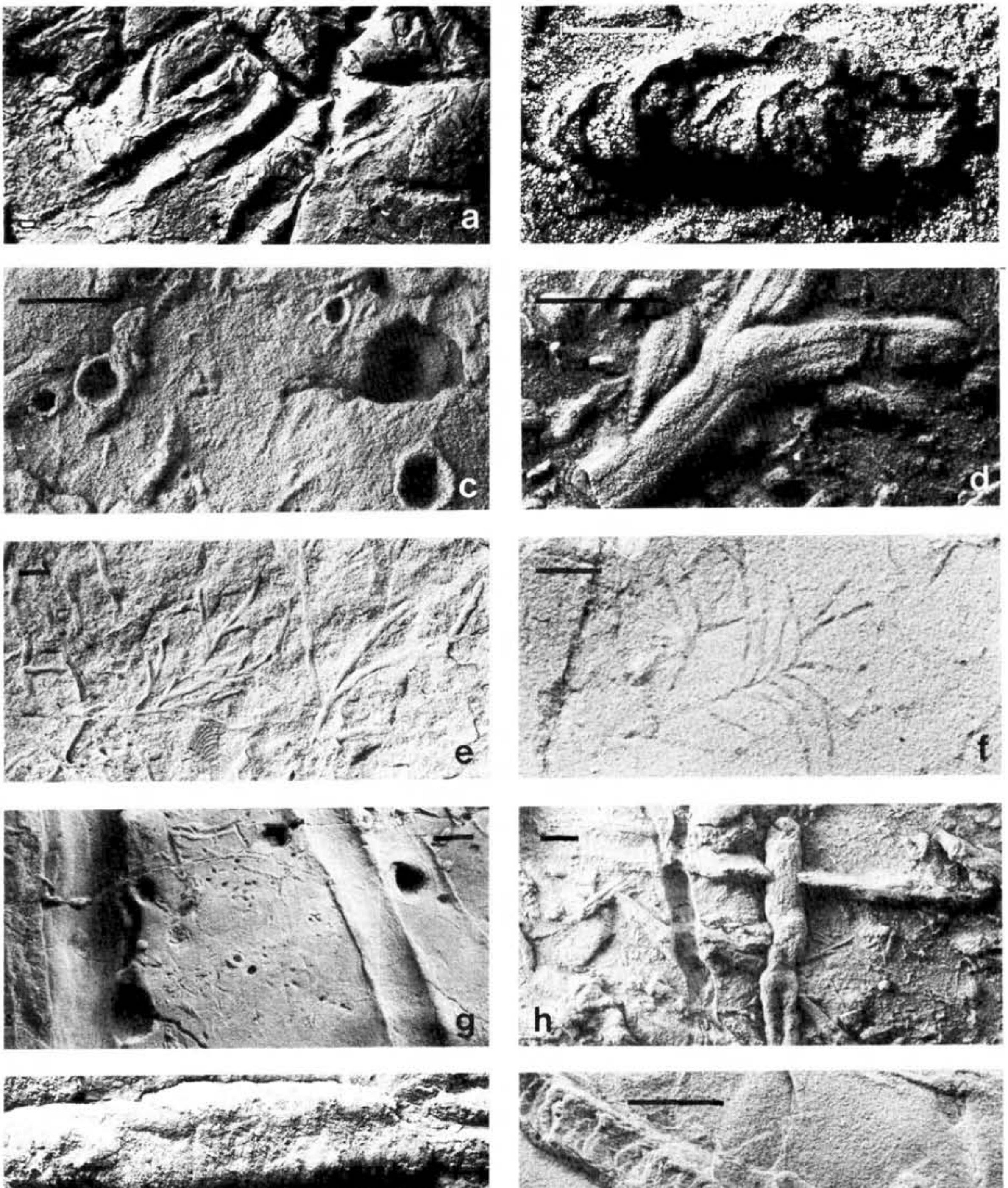
Origin of name: Devil's Dingle, type locality.
Diagnosis: Unbranched horizontal burrow, circular to elliptical in cross-section, diameter 2–2.5 mm, displaying symmetrically arranged irregular scratch marks at various points along the sides and behind the ovoid expanded burrow ends.
Holotype: H.M. G159.55.
Paratypes: H.M. G159.56–57.
Occurrence: Hughley Shales (Lower Silurian, Upper Llandovery, *griestonienis* Zone/C_5 Substage) of Devil's Dingle dam site, near Buildwas, Shropshire (Grid. ref. SJ 639 052). On the top of sandstone units.
Description: The 3 specimens of the hypodigm preserve 6 separate examples of burrows with the scratch marks characteristic of this ichnogenus. Burrow width in unscratched areas varies from 1.8–3.0 mm, averaging 2.0–2.5 mm, and the cross-section is elliptical to circular. The burrow fill is the same as the matrix and there is evidence of backfill. The burrow may change level within the sandstone, but scratch marks only occur in burrows on top of the sandstone units.

One specimen (Fig. 11*d*) shows a series of 16 backwards pointing paired lateral scratch marks, about 0.2 mm wide and projecting up to 0.5 mm from the side of the burrow. The burrow then expands to a width of 3.5 mm before coming to an end. The terminal section is 6 mm long and displays small scratch marks laterally.

Other specimens show scratch marks only in the terminal part. The specimen in Fig. 11*e* shows a series of 0.2 mm broad scratch marks extending back from an expanded end section. Another specimen (Fig. 11*f*) shows a double set of scratch marks on an expanded area in the course of a 2 mm burrow. The scratches are 0.2–0.3 mm wide and 0.5 mm long.

FIG. 10. Trace fossils in sandstone units of the Hughley Shales. *d* from Hughley Brook tributary, others from Devil's Dingle. All specimens coated with ammonium chloride for photography. Scale bar represents 5 mm.

a, *Diplocraterion* (or *Corophioides*) on top of sandstone unit, cross sections, HM G159.45; *b*, *Diplocraterion* (or *Corophioides*) showing spreite, cross section, HM G159.46; *c*, *Skolithos*, tops of burrows, HM G159.47; *d*, *Scolicia*, on tool-marked surface, NUGD B; *e*, *f*, *Chondrites*, HM G159.48, HM G159.49, *g*, *Palaeophycus*, casts of burrows on top of sandstone units, HM G159.50; *h*, *Palaeophycus*, collapsed burrow on tool-marked surface, HM G159.51; *i*, *Palaeophycus*, with annulation, HM G159.52; *j*, *Palaeophycus*, with backfill, HM G159.53.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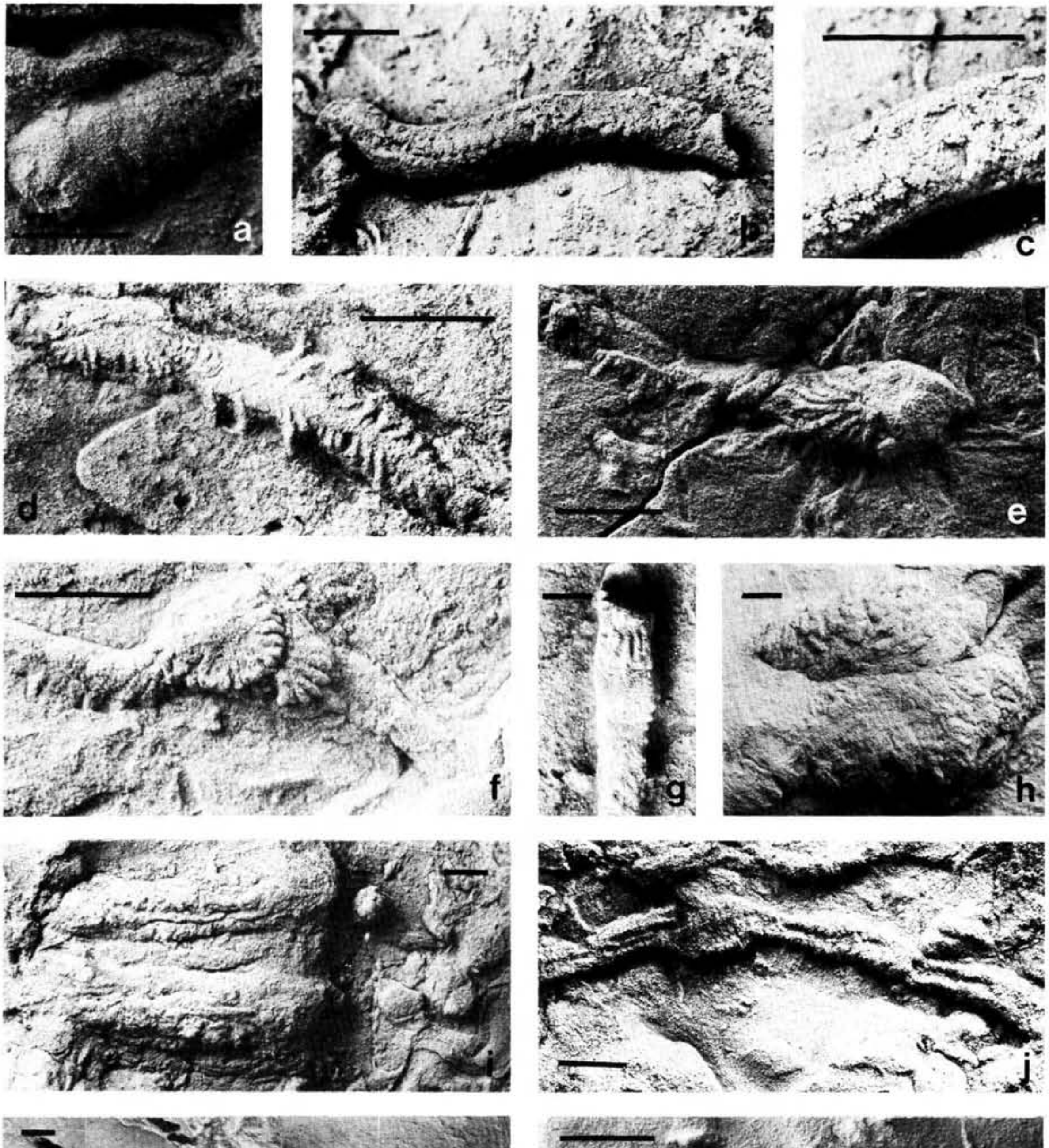
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Finally, Fig. 11g shows a specimen where the expanded end of the burrow is missing, but some longitudinal scratch marks form a collar round the burrow.

Interpretation: The trace-producing animal appears to have had a body 2–3 mm in diameter. We assume that the scratch marks were formed by paired appendages of some kind towards the rear end of the body (or the scratches would not be so clear). We propose that the animal normally did not require extensive leg kicks for progression through the sediment, but occasionally had to stabilize itself by extending its appendages, as in Fig. 11*f*.

Most scratch marks occur at expanded burrow ends, and these we interpret as points at which the animal changed level in the sediment (Fig. 12), as Osgood (1970, p. 379) suggested for *W. rugosa*. To do so, it extended its hind legs and pushed. The specimen illustrated in Fig. 11*f* may represent an abortive attempt to do this. Cross sections through the sandstone blocks did not reveal any level changes downwards at the scratched areas, so that the animal must have been moving up into the mud above, if our interpretation is correct. This is supported by the fact that the scratched areas are elevated above the general level of the burrow. The softer sediment could require a different locomotory technique, but we were unable to collect complete specimens because of the friable nature of the mudstone.

In most parts of the burrow, there are no scratch marks, and progression must have been effected by anterior appendages, peristalsis, or cilia, and the body erased all evidence of this activity.

The presence of paired appendages indicates an arthropod as the trace-producing animal. There are very small trilobites in the Hughley Shales fauna (Whittard 1938) that could produce a burrow of the appropriate size, but they might be expected to leave scratch marks all along the walls, and not just in some places.

Environmental interpretation. *Walcottia rugosa* occurs in the Cincinnatian (Upper Ordovician) of Ohio, which is ascribed to the *Cruziana* facies by Osgood (1970, p. 340).

Bilobates (Cubichnia, Repichnia)

Ichnogenus *Rusophycus* Hall 1852

One specimen on the base of a lamina within a sandstone unit (Fig. 11*h*) shows paired impressions, each element 19.5 mm long, up to 10 mm wide, and up to 5 cm deep, with radiating scratch marks. This conforms to the ichnogenus *Rusophycus*, and is probably a trilobite resting trace.

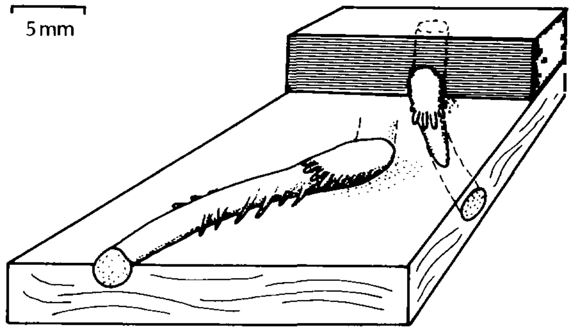

FIG. 12. *Walcottia devilsdingli* ichnosp. nov., stratonomic interpretation showing passage of trace from sandstone to mudstone above.

Ichnogenus *Cruziana* d'Orbigny 1842 (large form)

On the same slab as the *Rusophycus* is a longer paired furrow (Fig. 11*i*) probably formed by the same animal foraging. Each furrow is 37 mm long, and up to 13 mm wide. There is a median groove on each half of the trace and scratch marks on either side.

Cruziana (*Isopodichnus*) *problematica* (Schindewolf 1921)

Another specimen on a tooled surface (Fig. 11*j*) shows a more extended arthropod paired furrow, averaging 2.5 mm in breadth. There is a resting impression, 5 mm long and 4 mm broad at one point. Transverse scratch marks are just discernible. This trace was formed on a second-level tool-marked surface, barely 5 mm above the base of the sandstone unit, evidently a brief respite from the high energy current.

This specimen falls well outside the normally defined size range of *Cruziana* (width 0.5–8 cm, Häntzschel 1975, p. W55); and within that of *Isopodichnus* (width up to about 6 mm, Häntzschel 1975, p. W74; Trewin 1976). *Isopodichnus* is normally regarded as a facies indicator of the non-marine environment, which we clearly do not have here. On purely morphological criteria, the specimen could be named *Isopodichnus* (although it lacks evidence of

FIG. 11. Trace fossils in sandstone units of the Hughley Shales. All specimens from Devil's Dingle, and coated with ammonium chloride for photography. Scale bar represents 5 mm.

a, *Palaeophycus*, with body impression at end (?), HM G159.52; *b*, *Palaeophycus*, with impressions of dorsal scales, HM G159.54; *c*, Detail of above, HM G159.54; *d*, *Walcottia devilsdingli* ichnosp. nov., type specimen, HM G159.55; *e*, Ditto, paratype, HM G159.56; *f*, Ditto, paratype, HM G159.57; g, Ditto, paratype HM G159.55; *h*, *Rusophycus*, HM G159.58; *i*, *Cruziana* (large form), HM G159.58; *j*, *Cruziana* (*Isopodichnus*) *problematica*, on tool-marked surface, HM G159.59; *k*, *Diplichnites*, HM G159.60; *l*, Detail of above, HM G159.60.

the characteristic paired endings described by Trewin 1976). In this case, at least, the proposal by Bromley & Asgaard (1979) that *Isopodichnus* and small *Cruziana* should be included in *Cruziana problematica* (Schindewolf 1921) seems justified.

Ichnogenus *Diplichnites* Dawson 1873

Two parallel series of transverse scratch marks (Fig. 11*k*,*l*) probably represent a trilobite walking trace. Each scratch is 0.5–3.0 mm long, succeeding scratches are spaced 1.5–2.0 mm apart, and the whole trackway is about 12 mm wide, the clear central space being 5–7 mm wide. Each series appears to consist of a longer outer scratch, sometimes forking laterally (Fig. 11*l*), and a shorter inner impression.

Environmental interpretation. *Rusophycus*, *Cruziana* and *Diplichnites* are characteristic of Seilacher's *Cruziana* facies (sublittoral, marine).

Discussion

Environment of deposition

Several lines of evidence indicate that the sandstone beds were deposited in a shelf environment: palaeogeography, shelly fauna, trace fossils and certain aspects of the sedimentology.

Current palaeogeographic models (Ziegler *et al.* 1968*b*; Ziegler 1970; Bridges 1975) place the Hughley Shales outcrop approximately three-quarters of the way out on the Upper Telychian shelf (Fig. 13). This is also confirmed by the fine condition of most of the fossils collected from interbedded mudstones, suggesting that they were indigenous to this normally muddy shelf habitat. The faunas have been placed in the *Clorinda*, or Marginal *Clorinda* community (Ziegler *et al.* 1968*b*), both of which are relatively deep-water shelf faunal associations.

The trace fossil evidence also points to a position well offshore on the shelf. *Diplocraterion* (or *Corophioides*) and *Skolithos* occur in littoral to sublittoral environments, *Scolicia* in the sublittoral to deep-water zones, and *Rusophycus*, *Cruziana*, *Diplichnites*, and possible *Walcottia*, characterize Seilacher's sublittoral *Cruziana* Facies. There are none of the meandering and reticulate feeding traces typical of normal deep-water turbidite facies. Thus, the trace fossils indicate a position on the more distal shelf.

Superficially, the interbedded sandstones resemble distal turbidites with an apparent Bouma sequence of divisions A, C, D and E (Bouma 1962). Evidence against a palaeoslope-driven 'deep-sea' turbidite interpretation rests initially on the palaeogeographic/faunal setting where gravity-driven turbidity flows are not likely. The lateral similarity of Hughley Shales lithofacies within the Upper Telychian (over many tens of km) is not consistent with a fan turbidite model. We suggest that shelf storms provide a mechanism for the formation of these sandstone units.

Shelf storm depositional mechanisms

Shelf sediment dispersal is a complex process (Creager & Sternberg 1972; Swift 1976). Information on recent shelf storm events is scant (Hayes 1967; Draper 1967; Reineck & Singh 1972). The deposits depend on storm type, its timing and direction, hydrography and water depth. These in turn influence bottom currents, depth of storm wave base, sediment supply and sediment suspension in the overlying water column. Mooers (1976) recognized 3 broad categories of atmospheric disturbance: (1) local short-lived diurnal breeze systems; (2) larger atmospheric disturbances that may operate over a period of days; (3) latitude-continent induced pressure cell regimes that persist on a seasonal basis. Clearly the depositional record for each of these events will be different.

Storms produce surface currents by wind-stress and may generate powerful unidirectional currents down to considerable depths. Draper (1976) recorded significantly high oscillatory particle speeds occurring at depths in excess of 150 m in response to storm waves on the continental shelf margin off NW Europe.

Storm surge currents, induced by a hydraulic head of landward-directed water during the height and early waning stages of storms, are believed to be a major transportation mechanism for shelf sediment. They may be directed both onshore and offshore, and are the most powerful traction currents associated with storms. However, the storm surge ebb current is more important since it transports sediment from a shoreface environment onshelf (Gadow & Reineck 1969; Reineck & Singh 1972). Hayes (1967) noted that Hurricane Carla transported sand out onto the shelf off Texas for at least 15 km where it was deposited as a graded unit. He invoked transport by a density current produced by a storm surge ebb. Reineck & Singh (1972, p. 136) noted that storms in the North Sea charge the water with a sand suspension load far out onto the shelf, and concluded that laminated sheet sands could be deposited from suspension clouds in slowly moving waters (current velocity <20 cm/s). Rip current systems, channelled at right angles to the coast, may influence position and directionality of these events.

Ancient shelf storm deposits

Many ancient shelf sand sheets associated with muddy facies and dominated by parallel and ripple lamination have been interpreted as shelf storm deposits (Goldring & Bridges 1973; Bridges 1975; Harms *et al.* 1975; Walker 1979; Brenchley *et al.*

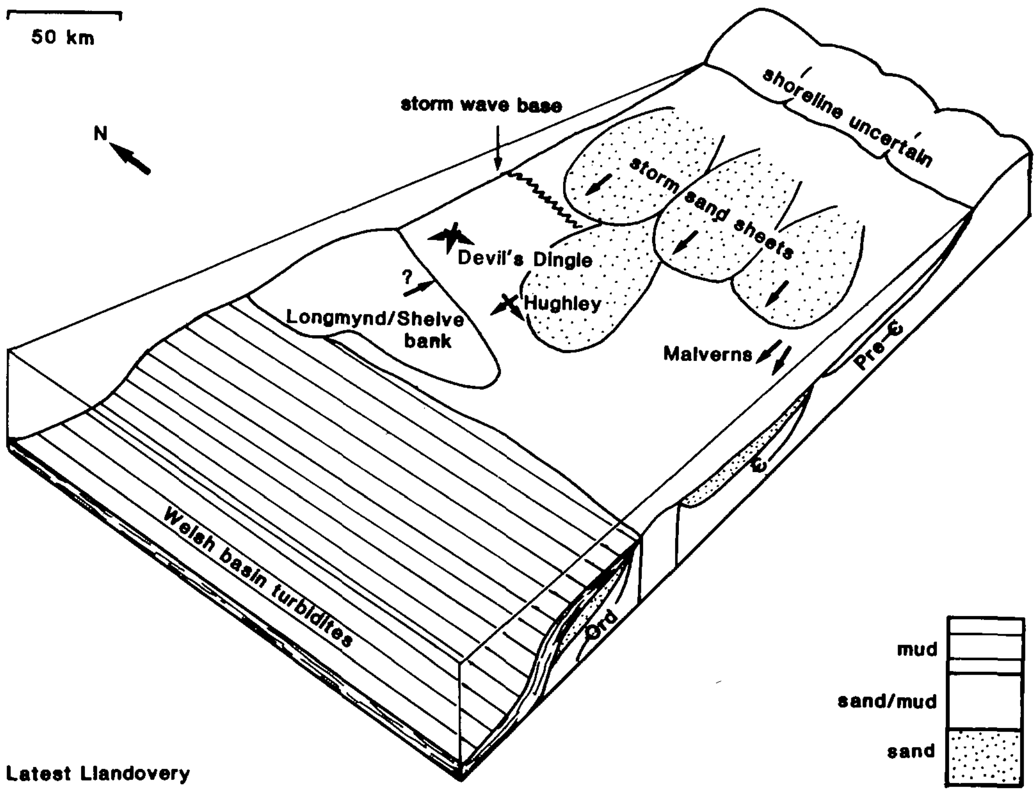

FIG. 13. Palaeogeographic model of the central Welsh Borders region during the latest Llandovery (Telychian, C_5 Substage) showing generalized sediment distribution and palaeocurrents. The limit of deepened wave base effects on storm-induced turbidites is indicated. Palaeogeography based on Bridges (1975).

1979; Bourgeois 1980; Greensmith *et al.* 1980). In most cases, the muddy units contain a diverse assemblage of benthonic fossils and these are represented as clasts in the sandy units with delicate detail preserved (Goldring & Bridges 1973). The bases of the sandy units are often scoured and the tops bioturbated. The units are normally 10–500 cm thick, display horizontally laminated fine sands and hummocky cross stratification, and grade laterally (and perhaps vertically) into shoreface sediments (Walker 1979).

Storm bed morphology depends on sedimentary location. Deposition may occur from suspension fallout and density current bedload together with modification by a deepened wave base (producing hummocky cross stratification), or from density currents and suspension fallout that travel below the deepened wave base (Walker 1979, p. 86, fig. 15).

The Hughley sandstones as shelf storm deposits

The sedimentary evidence suggests that the Hughley Shales sandstones belong to the category of storm beds deposited below deepened storm wave base. The units are far thinner than most of those previously described, and there are no features suggestive of oscillatory particle motion. No hummocky cross stratification has been recognized, although irregularly undulose bed bases may attest to a short-lived early erosive/depositional event of a similar kind. The climbing ripple sets indicate variable bottom current flow directions largely similar to those measured from underlying tool-marked bed bases.

Whilst superfically similar to typical distal fan palaeoslope-associated turbidites, the sandstones show important differences: the spatio-temporal variability of internal coquinas and coarse clastic lenses, the low-relief irregular undulations on the bed bases, a dominance of parallel lamination (lower flow regime), and the wide palaeocurrent array.

The dominant fine sand was probably derived from local on-shelf sources, as stressed by Levell (1980) for the Precambrian deposits of Finnmark. The well-preserved whole fossils and bioclasts were also probably not transported far, as suggested by the 'pluck structures'. Deposition was probably rapid, as suggested by possible contemporaneous dewatering structures (upturned ruptured laminae with planar scoured tops).

The coarse layers were probably produced by storm surge traction currents, and most of the fine sediment size-range may have been deposited from suspension (Reineck & Singh 1972). The range and nature of the tools marks, the presence of non-basal coarse lags, and the gutter casts indicate that bottom traction currents must have been relatively forceful, but often of varying and inconstant directions. Similar gutter casts from the Upper Telychian (C_6) Wych Beds of the Malvern Hills, Gloucestershire, have also been interpreted as produced by storm surge currents (Bridges 1972).

Palaeocurrent evidence (Figs 1, 13) suggests that shore-parallel and offshore-directed density currents predominated. Johnson (1978, p. 221) also recognized that shelf storms are accompanied by coast-parallel residual currents, although traction currents caused by the offshore-directed storm surge ebb are most important.

The periodicity of the Upper Llandovery sandstones described suggests an episodic scale of ≥ 1 every several thousand years (from approximate rates of mudstone deposition, Swift 1976). Such rare events would preclude a seasonal event and suggest that large, infrequent storms were responsible. Such storm deposits will be favourably preserved in the record (Ager 1973).

Depositional model for the Hughley Shales

1. Storm surge ebb traction currents transport nearer shoreface sediments as bedload offshore and locally transport indigenous coarser bioclasts during the height and early waning stages of a major (rare) storm. Associated with this are tool marking and guttering of the underlying cohesive muds and deposition of discontinuous coarse layers. The timing of the main storm surge ebb current and position on-shelf may determine whether scours and coarse lenses are basal or internal to the sand sheets.
2. As the storm wanes, sediment brought out on to the shelf in the turbulent storm wave-affected zone starts to settle, producing laminated sands. This suspension fall-out is contemporaneously modified by the now waning storm surge ebb traction currents, producing climbing ripple sets. Deepened wave base therefore only indirectly affects these sand bodies by providing a mechanism for prolonging suspension of fine sands and assisting their transport far out on the shelf.
3. Current activity decreases, allowing parallel laminated sediments to form as the finest sands and silts eventually settle out of suspension. This phase may last over a period of days. At this stage, infaunal and epifaunal re-colonization commences, and delicate epifaunal traces (e.g. *Diplichnites*) are preserved. Finally, 'background' mud sedimentation re-starts, allowing further colonization and modification by infauna.

Conclusion

The Lower Silurian Hughley Shales of Shropshire consist of interbedded mudstones and thin sandstones. The formation contains a range of body fossils and trace fossils that indicate deposition in the deeper sublittoral shelf zone. Transported benthonic fossils typical of the distal shelf *Clorinda* Community of Ziegler (1965) are preserved in poor to good condition within the thin sandstone units, and the trace fossil assemblage, including *Diplocraterion* (or *Corophioides*), *Rusophycus, Cruziana, Walcottia*, and *Diplichnites* is typical of Seilacher's *Cruziana* Facies. Spectacular tool marks on the bases of sandstone units include many identifiable forms, produced by horn corals, coral colonies, crinoids, brachiopods and trilobites.

A depositional model is proposed that invokes rapid deposition of the sandstone layers from turbidite-like flow induced by storm surge ebb currents and from suspension. The significant feature of the Hughley Shales storm beds is that they are situated more distally on the shelf than most previously described examples, and they provide a good selection of the features to be expected in this regime elsewhere.

Distal shelf storm beds may be distinguished from proximal ones by the presence of palaeontological 'depth' indicators (e.g. brachiopods, trace fossils) that suggest a position well offshore, the small bed thickness, the absence or poor development of hummocky cross stratification, and the absence of other indications of wave modification such as wave ripples.

Distal shelf storm beds may be distinguished from typical fan turbidites by the common occurrence of lags and coquinas within the sand unit, and the wide spread of palaeocurrents for each event.

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References

AGER, D. V. 1973. *The Nature of the Stratigraphic Record.* Macmillan, London, 114 pp.

ALPERT, S. P. 1975. *Planolites* and *Skolithos* from the Upper Precambrian–Lower Cambrian, White–Inyo Mountains, California. *J. Paleont.* **49,** 508–21.

BASSETT, M. G., COCKS, L. R. M., HOLLAND, C. H., RICKARDS, R. B. & WARREN, P. T. 1975. The type Wenlock Series. *Rep. Inst. geol. Sci. London,* **75/13,** 1–19.

BATES, D. E. B. 1974. Probable orthocone skip and roll marks from the Aberystwyth Grits. *Geol. Mag.* **111,** 31–4.

BENTON, M. J. & TREWIN, N. H. 1978. Discussion and comments on Nicholson's 1872 manuscript 'Contributions to the study of Errant Annelides of the Older Palaeozoic rocks'. *Publs. Dep. Geol. Miner. Univ. Aberdeen,* **1,** 1–16.

BLANCKENHORN, M. 1916. Organische Reste im mittleren Buntsandstein Hessens. *Sitzungsber. Ges. Beförd. gesamten Naturwiss. Marburg,* **1916,** 21–43.

BOUMA, A. H. 1962. - *of some Flysch Deposits.* Elsevier, Amsterdam, 168 pp.

BOURGEOIS, J. 1980. A transgressive shelf sequence exhibiting hummocky cross stratification: the Cape Sebastian Sandstone (Upper Cretaceous), Southwest Oregon. *J. sediment. Petrol.* **50,** 681–702.

BRENCHLEY, P. J., NEWALL, G. & STANISTREET, I. G. 1979. A storm surge origin for sandstone beds in an epicontinental platform sequence, Ordovician, Norway. *Sediment. Geol.* **22,** 185–217.

BRIDGES, P. H. 1972. The significance of toolmarks on a Silurian erosional furrow. *Geol. Mag.* **109,** 405–10.

—— 1975. The transgression of a hard substrate shelf: the Llandovery (Lower Silurian) of the Welsh Borderland. *J. sediment. Petrol.* **45,** 79–94.

BROMLEY, R. & ASGAARD, U. 1979. Triassic freshwater ichnocoenoses from Carlsberg Fjord, East Greenland. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **28,** 39–80.

CHAMBERLAIN, C. K. 1971. Morphology and ethology of trace fossils from the Ouachita Mountains, southeastern Oklahoma. *J. Paleont.* **45,** 212–46.

COCKS, L. R. M. & RICKARDS, R. B. 1969. Five boreholes in Shropshire and the relationships of shelly and graptolitic facies in the Lower Silurian. *J. geol. Soc. London,* **124,** 213–38.

—— & WALTON, G. 1968. A large temporary exposure in the Lower Silurian of Shropshire. *Geol. Mag.* **105,** 390–7.

CREAGER, J. S. & STERNBERG, R. W. 1972. Some specific problems in understanding bottom sediment distribution and dispersal on the continental shelf. *In*: SWIFT, D. J. P., DUANE, D. B. & PILKEY, O. H. (eds). *Shelf Sediment Transport, Process and Pattern.* Dowden, Hutchinson and Ross, Stroudsberg, Pa., 347–61.

DRAPER, L. 1967. Wave activity at the sea-bed around northwestern Europe. *Marine Geol.* **5,** 133–40.

DŻUŁYŃSKI, S. & WALTON, E. K. 1965. Sedimentary features of flysch and greywackes. *Developments in Sedimentology,* **7,** 1–274.

EARP, J. R. & HAINS, B. A. 1971. *British Regional Geology: The Welsh Borderland.* London, HMSO, 1–118.

GADOW, S. & REINECK, H. E. 1969. Ablandiger Sandtransporten bei Stormfluten. *Senckenberg. Marit.* **1,** 63–78.

GOLDRING, R. & BRIDGES, P. 1973. Sublittoral sheet sandstones. *J. sediment. Petrol.* **43,** 736–47.

GREENSMITH, J. T., RAWSON, P. F. & SHALABY, S. E. 1980. An association of minor fining-upward cycles and aligned gutter marks in the Middle Lias (Lower Jurassic) of the Yorkshire coast. *Proc. Yorkshire geol. Soc.* **42,** 525–38.

HAKES, W. G. 1977. Trace fossils in late Pennsylvanian cyclothems, Kansas. *In*: CRIMES, T. P. & HARPER, J. C. (eds). *Trace Fossils, 2.* Seel House Press, Liverpool, 209–26.

HÄNTZSCHEL, W. 1975. Miscellanea, Supplement 1, Trace Fossils and Problematica. *Treatise on Invertebrate Paleontology* (ed. C. Teichert), Part W, 1–269.

HARMS, J. C., SOUTHARD, J. B., SPEARING, D. R. & WALKER, R. G. 1975. Depositional environments as interpreted from primary sedimentary structures and stratification sequences. *Soc. Econ. Paleont. Mineral., Short Course* **2,** 1–161.

HATTIN, D. E. & FREY, R. W. 1969. Facies relations of *Crossopodia* sp. a trace fossil from the Upper Cretaceous of Kansas. *J. Paleont.* **43,** 1435–40.

HAYES, M. O. 1967. Hurricanes as geological agents: case studies of hurricanes Carla 1961, and Cindy 1963. *Rep. Invest. Texas Bur. econ. Geol.* **61,** 1–54.

JOHNSON, H. D. 1978. Shallow siliciclastic seas. *In*: READING, H. G. (ed.). *Sedimentary Environments and Facies.* Blackwell Scientific Publ., Oxford, 207–58.

KELLING, G. & WHITAKER, J. H. McD. 1970. Tool marks made by ribbed orthoconic nautiloids. *J. Geol. Chicago,* **78,** 371–4.

KNOX, R. W. O'B. 1973. Ichnogenus *Corophioides. Lethaia,* **6,** 133–46.

LEVELL, B. K. 1980. Evidence for currents associated with waves in Late Precambrian shelf deposits from Finnmark, North Norway. *Sedimentology,* **27,** 153–66.

MILLER, S. A. & DYER, C. B. 1878. Contributions to palaeontology, no. 1. *J. Cincinnati Soc. nat. Hist.* **1,** 24–39.

MOOERS, C. N. K. 1976. Wind-driven currents on the continental margin. *In*: STANLEY, D. J. & SWIFT, D. J. P. (eds). *Marine Sediment Transport and Environmental Management.* Wiley, New York, 29–52.

OSGOOD, R. G. 1970. Trace fossils of the Cincinnati area. *Palaeontogr. Americana,* **6,** 277–444.

PETTIBONE, M. H. 1953. *Some Scale-bearing Polychaetes of Puget Sound and Adjacent Waters.* Univ. Washington Press, Seattle, 1–89.

POCOCK, R. W., WHITEHEAD, T. H., WEDD, C. B. & ROBERTSON, T. 1938. Shrewsbury district. *Mem. geol. Surv. U.K.* **152,** 1–297.

RAAF, J. F. M. DE, BOERSMA, J. R. & GELDER, A. VAN. 1977. Wave generated structures from a shallow marine succession. Lower Carboniferous, County Cork, Ireland. *Sedimentology,* **24,** 451–84.

REINECK, H. -E. & SINGH, I. B. 1972. Genesis of laminated sand and graded rhythmites in storm sand layers of shelf mud. *Sedimentology,* **18,** 123–8.

—— & —— 1973. *Depositional Sedimentary Environments with Reference to Terrigenous Clastics.* Springer-Verlag, Berlin, 439 pp.

SMITH, S. 1930. Some Valentian corals from Shropshire and Montgomeryshire, with a note on a new stromatoporoid. *Q. J. geol. Soc. London,* **86,** 291–330.

SWIFT, D. J. P. 1976. Continental shelf sedimentation. *In*: STANLEY, D. J. & SWIFT, D. J. P. (eds). *Marine Sediment Transport and Environmental Management.* Wiley, New York, 311–50.

TREWIN, N. H. 1976. *Isopodichnus* in a trace fossil assemblage from the Old Red Sandstone. *Lethaia,* **9,** 29–37.

—— 1979. Transported graptolites and associated tool marks from Grieston Quarry, Innerleithen, Peeblesshire. *Scott. J. Geol.* **15,** 287–92.

WALKER, R. G. 1979. Facies models 7. Shallow marine sands. *In*: WALKER, R. G. (ed.). *Facies Models*, Geoscience Canada, 75–89.

WHITTARD, W. F. 1928. The stratigraphy of the Valentian rocks of Shropshire. The main outcrop. *Q. J. geol. Soc. London*, **83,** 737–59.

—— 1938. The Upper Valentian trilobite fauna of Shropshire. *Ann. Mag. nat. Hist. London*, ser. 11, **1,** 85–140.

—— 1952. A geology of South Shropshire. *Proc. Geol. Assoc. London*, **63,** 143–97.

ZIEGLER, A. M. 1965. Silurian communities and their environmental significance. *Nature, London*, **207,** 270–2.

—— 1970. Geosynclinal development of the British Isles during the Silurian period. *J. Geol. Chicago*, **78,** 445–79.

——, COCKS, L. R. M. & BAMBACH, R. K. 1968*a*. The composition and structure of Lower Silurian marine communities. *Lethaia*, **1,** 1–27.

——, —— & MCKERROW, W. S. 1968*b*. The Llandovery transgression of the Welsh Borderland. *Palaeontology*, **11,** 736–82.

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