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STRATIGRAPHY, REEF DEVELOPMENT AND TRACE FOSSILS OF THE UPPER SILURIAN DOURO FORMATION IN THE SOUTHEASTERN CANADIAN ARCTIC ISLANDS

by

Guy Michael Narbonne

A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for the degree of Ph.D. in Geology

UNIVERSITY OF OTTAWA
OTTAWA, CANADA, 1981

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UNIVERSITY OF OTTAWA

Pooh and Piglet Go Hunting

Suddenly Winnie-the-Pooh stopped, and pointed excitedly in front of him. "*Look!*"

"*What?*" said Piglet, with a jump. And then, to show that he hadn't been frightened, he jumped up and down in an exercising sort of way.

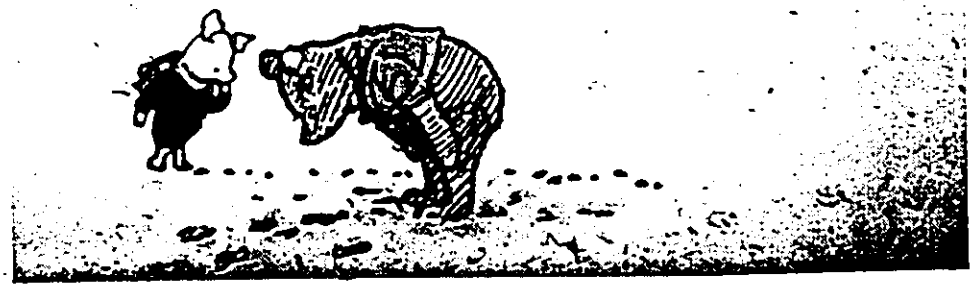
"The tracks!" said Pooh. "*A third animal has joined the other two!*"

"Pooh!" cried Piglet. "Do you think it is another Woozle?"

"No," said Pooh, "because it makes different marks. It is either Two Woozles and one, as it might be, Wizzle, or Two, as it might be, Wizzles, and one, if so it is, Woozle."

And then Winnie-the-Pooh stopped again, and licked the tip of his nose in a cooling manner, for he was feeling hot and anxious. "Do you see, Piglet? Look at their tracks! Three, as it were, Woozles, and one, as it was, Wizzle. *Another Woozle has joined them!*"

Winnie-the-Pooh



Frontispiece

GENERAL ABSTRACT

The Read Bay Formation on Somerset Island, the lower part of member A of the Read Bay Formation on Cornwallis Island, and the Douro Formation on Devon Island represent a single widespread unit which should be termed the Douro Formation throughout these three islands. The Douro Formation is of Late Silurian (Ludlow) age, and consists predominantly of rubbly (nodular) limestone with a shelly fauna dominated by smooth-shelled brachiopods. The presence of argillaceous divisions and coral-rich zones provides two independent, but complementary criteria which can be used to correlate sections of the formation throughout the southeastern Canadian Arctic Islands. The argillaceous detritus was most likely derived from a northerly source area. The Douro Formation was deposited in subtidal shelf environments, probably in warm, tranquil, turbid waters of normal or near-normal marine salinities. On Somerset Island, the Douro Formation is underlain by the Cape Storm/Leopold Formations and is overlain by the Somerset Island Formation; these underlying and overlying units were deposited in tidal flat environments. The two deepest stages of the Douro transgression were characterized by a diverse fossil assemblage and sporadic reefal development, whereas shallower deposits were characterized by abundant intraclasts and rare oolites, oncolites and stromatolites.

The reefs of the Douro Formation are the first reported Silurian sponge reefs. These relatively small (5-35 m in diameter) mound-shaped structures contain, on average, 35% lithistid demosponges. Each reef is underlain by a lens of crinoidal wackestone to grainstone rich in crinoid holdfasts; trepostomate bryozoans, solenoporid algae and rhynchonellid brachiopods are locally common. The main mass of each reef consists of lime mudstone with abundant lithistid sponges. A thin layer of wackestone with abundant tabulate and rugose corals and fewer lithistid sponges, calcareous algae, trepostomate bryozoans and stromatoporoids caps each reef. Reefs are commonly surrounded by irregular haloes of crinoidal debris; the abundance and diversity of all fossil groups decreases regularly with distance from the reef. The Douro Sponge Reefs were relatively low structures, with a maximum topographic relief of about 3 m. Much of the reefal lime mud was transported from inter-reefal areas, but significant quantities were produced on the reefs. Reefs underwent synsedimentary cementation, bioerosion and minor storm erosion. The originally siliceous spicules of the lithistid sponges were dissolved and later infilled with sparry calcite. Fabrics and compositions of sparry calcite in cavities record three generations of meteoric cementation. These sponge reefs formed during a geologic period in which coral faunas were diverse. As a consequence, sponge reefs

were much more restricted in environment and distribution than they were during periods of evolutionary decline of corals. The Douro Reefs are similar to some Ordovician, Jurassic and Holocene sponge reefs in that the sponges occurred mainly in colonization communities which were later replaced by coral-rich climax communities.

Upper Silurian strata on Somerset, Cornwallis and Devon Islands contain numerous trace fossils. A Polarichnus - Bergaueria association characterizes intertidal limestones and dolostones (Cape Storm and Leopold Formations); a Fuersichnus - Uchirites association characterizes subtidal shelf limestones (Douro Formation); and a Scalarituba association characterizes basin slope limestones (tongue of the ?Cape Phillips Formation). Features resulting from formational and preservational processes of trace fossils suggest that lime mud substrates were generally firm, whereas substrates composed of silt-sized carbonates ranged from firm to thixotropic. Subtidal planar-bedded calcisiltite exhibits a diverse trace fossil assemblage similar to those reported from bathymetrically-equivalent siliciclastic deposits. In contrast, extensive diagenetic modification in the subtidal rubbly calcilutite resulted in a low diversity assemblage restricted to infaunal feeding and dwelling traces. Although the mineralogic composition of the substrate

is probably relatively unimportant in controlling the distribution of trace-making organisms, the greater susceptibility of carbonates to early and late diagenetic processes can significantly affect the nature of their trace fossil assemblages.

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GENERAL INTRODUCTION

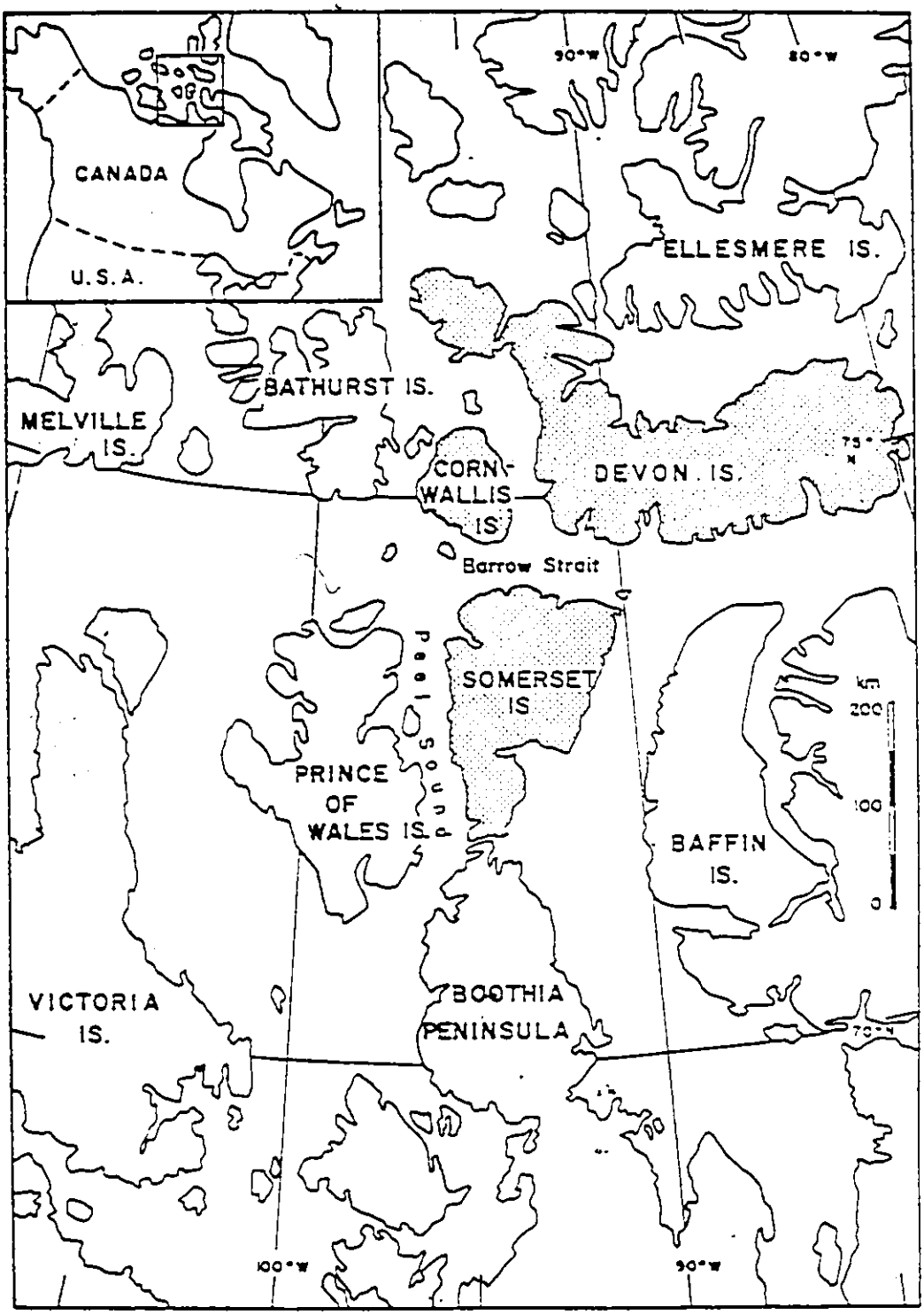
GENERAL INTRODUCTION

LOCATION AND ACCESS

Somerset, Cornwallis and Devon Islands are located in the eastern part of the District of Franklin, Northwest Territories (Text-fig. 1). They exhibit moderate relief; excellent bedrock exposure occurs along sea cliffs and in river gorges. Most geologic field work is carried out during June, July and August, the only months in which the mean temperature exceeds 0°C. Details of the history, physiography, climate and wildlife of the region can be found in Thorsteinsson (1958) and Fortier et al. (1963).

Resolute, a small village on southern Cornwallis Island, is the only permanent settlement in the region. Resolute is served by commercial flights from Montreal, Winnipeg and Edmonton. Field camps were reached by single- or twin-Otter flights from Resolute; landings were made by ski on the snow or with balloon tires on gravel. Local transport was primarily by foot, with limited use of Honda 90 ATC bikes, a Bell G-4A helicopter and a Hughes 500-C helicopter.

The project concentrated on southeastern Somerset Island; sections on southeastern Cornwallis Island, southwestern Devon Island and northwestern Devon Island were examined in less detail.



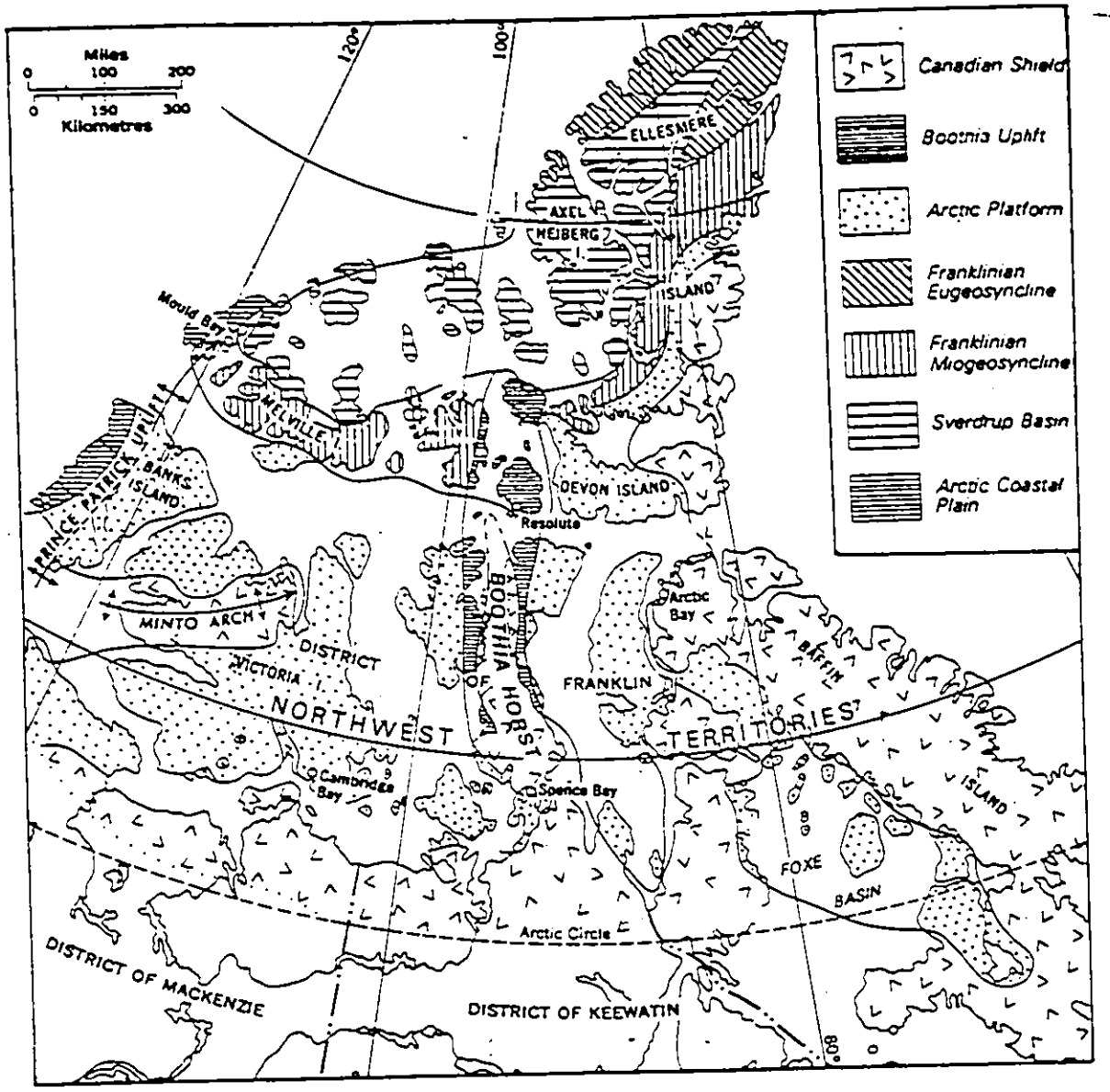
Text-fig. 1. Location of Somerset, Cornwallis and Devon Islands in the southeastern Canadian Arctic Islands (from Gibling 1978).

GENERAL GEOLOGY

The geologic history of the Arctic Islands has been summarized by Thorsteinsson and Tozer (1970), Daae and Rutgers (1975) and Kerr (1977). The reader is referred to these papers (and references therein) for more detailed accounts of the geology of the region.

Study areas lie within two major geologic provinces: the Arctic Platform and the Boothia Uplift (Text-fig. 2). The Arctic Platform consists of predominantly undeformed, Lower and Middle Paleozoic strata. The Boothia Uplift is cored by the Boothia Horst, a northwards extension of Churchill gneisses of the Canadian Shield. The horst was uplifted several times during the Proterozoic and Early-Middle Paleozoic (Kerr 1977). Major uplift during the late Ludlovian, Pridolian and Gedinnian (Late Silurian - Early Devonian) resulted in the formation of the Cornwallis Fold Belt, a north-plunging anticlinorium of strongly folded and faulted Lower Paleozoic strata. The Cornwallis Fold Belt flanks the Boothia Horst on Somerset and Prince of Wales Islands and overlies it on Cornwallis and northern Devon Islands (Text-fig. 2).

Lower Paleozoic strata on Somerset Island are approximately 2 km thick (Miall and Kerr 1980); similar or greater thicknesses are present on Devon and Cornwallis Islands. During most of the Silurian (Llandoverian-Late Ludlovian)



Text-fig. 2. Geologic provinces of the Canadian Arctic Islands (modified from Thorsteinsson and Tozer 1970).

platform carbonates of the Allen Bay Formation, Cape Storm/ Leopold Formations and member A of the Read Bay Formation were deposited throughout Somerset, Devon and southern Cornwallis Islands. Uplift of the Boothia Horst in the late Ludlovian, Pridolian and Gedinnian ended this pattern of stable shelf carbonate deposition, and resulted in deposition of a variety of regressive carbonate and clastic sequences on the three islands (Table 1).

SCOPE OF THE PROJECT

The University of Ottawa Group has been engaged in geologic studies of the southern Arctic Islands continuously since 1964. Studies have focussed on the Upper Silurian-Lower Devonian succession of Somerset Island. All Upper Silurian strata on Somerset Island were formerly referred to the Read Bay Formation of Thorsteinsson and Fortier (1954), but work by Jones (1974), Jones and Dixon (1975, 1977), Reinson et al. (1976), Miall and Kerr (1977), Miall et al. (1978), Gibling (1978), Savelle (1978) and Mayr (1978) has shown that this unit comprises several distinct formations. As a result, the once heterogeneous Read Bay Formation has been restricted to a thinner, relatively homogeneous succession of fossiliferous rubbly (nodular) limestones closely comparable to the Douro Formation (Thorsteinsson 1963) of Devon Island.

AGE	FORMATION AND THICKNESS	PREDOMINANT LITHOLOGIES	PREDOMINANT ENVIRONMENT
Upper Silurian to Lower Devonian	Peel Sound (600 m)	Conglomerate, sandstone	Fluvial
Upper Silurian	Somerset Island (150-400 m)	Dolostone, limestone, siltstone	Tidal flat
Upper Silurian	Read Bay (170-275 m)	Limestone	Subtidal shelf
Upper Silurian	Cape Storm/Leopold (120-240 m) (400 m)	Dolostone, limestone, sandstone	Tidal flat
Lower to Middle Silurian	Cape Crauford (580 m)	Dolostone, evaporite	Tidal flat
Upper Ordovician to Middle Silurian	Allen Bay (550-1050 m)	Dolostone	Tidal flat to subtidal shelf

Table 1. Silurian stratigraphy of Somerset Island. Data from Miall and Gibling (1978), Dixon and Jones (1978) and Miall and Kerr (1980).

Although Jones (1974), Gibling (1978) and Savelle (1978) had studied Upper Silurian deposits on northern, western and southern Somerset Island, the geology of the east coast had not yet been studied in detail. Scattered geologic observations and fossil collections made during the voyages of Parry (1826), Ross (1835) and McClintock (1859) had established the presence of Silurian limestone and evaporites in this area, and Blackadar (1963a) and Norris (1963) had studied the east coast of Somerset Island during June 1955, referring the strata to the Read Bay Formation. However the internal stratigraphy of these strata, and their relationship to the four members of the Read Bay Formation in the type area remained unknown.

During the summers of 1975 and 1976, the author carried out detailed field studies of the geology of southeastern Somerset Island. In order to better understand the regional relationships of these strata, the author also examined sections on southeastern Cornwallis Island (August 1976 - in conjunction with M.R. Gibling) and on western Devon Island (August 1978 - in conjunction with Drs. R. Thorsteinsson and U. Mayr).

Two major aims of this project were as follows:

1) Determination of the stratigraphy of the Read Bay Formation on southeastern Somerset Island and comparison with equivalent strata elsewhere in the Arctic Islands.

2) Analysis of the paleoecology and sedimentology of the formation in order to elucidate its paleoenvironmental history.

The first of these aims was carried out as originally planned. Investigation of the paleoecology and sedimentology of the formation revealed that most variations in body fossils and lithotypes can be related to the sporadic development of lithistid sponge reefs. Trace fossils are abundant in the Read Bay Formation and immediately underlying units, and form a valuable tool in paleoenvironmental analysis.

As the study progressed, it focussed increasingly on these three main aspects of the formation: its lithostratigraphy, its reefs and related deposits, and its trace fossils. These subjects are substantially inter-related; the lithostratigraphy provides the essential framework for the other two studies, and the three subjects collectively contribute to the paleoenvironmental and paleogeographic interpretation of this lithic succession. However, the three subjects can be presented logically as discrete, independent studies, and this three-part format was chosen as more appropriate for this study than a more conventional thesis format.

For convenience, a "General Abstract" summarizes the significant contributions of the study as a whole, and a "General Introduction" provides brief background information applicable to the entire thesis. Each of the three subsequent

parts is an independent manuscript with a separate abstract, introduction and conclusion, and each is intended to be fully comprehensible without prior reading of the other parts. This has resulted in repetition of some stratigraphic and paleoenvironmental information, but different aspects of those subjects are emphasized in each of the three parts. To avoid extensive duplication, a combined list of references serves the entire thesis.

ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to my thesis supervisor, Dr. O.A. Dixon, for his continual aid and encouragement throughout every phase of this project. Dr. R. Thorsteinsson (I.S.P.G.) encouraged me to compare the Upper Silurian strata on Somerset Island with those present on Cornwallis and Devon Islands and provided a large amount of unpublished information on these successions. Dr. C.K. Chamberlain (Cities Service Ltd., Denver) and Dr. B. Jones (University of Alberta) reviewed an earlier version of Part III, offering numerous helpful suggestions. Helpful comments on the trace fossils were provided by Dr. R.W. Frey (University of Georgia) and Prof. A. Seilacher (University of Tübingen); Dr. N.P. James (Memorial University) provided helpful advice on diagenetic fabrics in the reefs. Drs. K.W. Westphal (University of Wisconsin-Madison) and R.C. Gutschick (University of Notre Dame) loaned type specimens to the author. Algae and bryozoans were identified by

Dr. B. Mamet (Université de Montréal) and Dr. T.E. Bolton (GSC) respectively. Exemplary field assistance was provided by Mr. M.I. Rupners, Mr. M.R. Clarke and Mr. T.A. Garagan. Mrs. E.G. Packard translated a critical article. Miss W.L. Storto typed the manuscript. Photographic illustrations are the work of Mr. E.W. Hearn.

Field support by the Polar Continental Shelf Project, the Natural Sciences and Engineering Research Council (N.S.E.R.C. Grant A-5121 to O.A. Dixon), the Department of Indian Affairs and Northern Development (through the University of Ottawa Northern Research Group) and the Geological Survey of Canada (Operation Boothia - Dr. J.W. Kerr; Operation Devon - Dr. R. Thorsteinsson and Dr. U. Mayr) is gratefully acknowledged. Further support to the author came through Ontario Graduate Scholarships (1976-78; 1979-80), a N.S.E.R.C. Postgraduate Scholarship (1978-79) and a Grant-in-Aid from the A.A.P.G. (1976).

I would like to thank my colleagues in the Boothia Uplift Project, especially Dr. M.R. Gibling, Mr. J.J. Packard and Mr. W.G. Parkins, for providing an effective forum for discussion of the concepts in this thesis. And lastly, but most importantly, I would like to express my greatest thanks to my wife, Roslyn Schwartz, without whom this project would have taken much longer to complete.

PART I

LITHOSTRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF THE UPPER SILURIAN DOURO FORMATION IN THE SOUTHEASTERN CANADIAN ARCTIC ISLANDS

LITHOSTRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF THE UPPER SILURIAN DOURO FORMATION IN THE SOUTHEASTERN CANADIAN ARCTIC ISLANDS

Abstract. The Douro Formation of northwestern Devon Island is a Ludlovian unit which consists predominantly of rubbly limestone with abundant smooth-shelled brachiopods. Similar strata on other arctic islands have previously been referred to the undivided Read Bay Formation (e.g. Somerset Island) or to the lower part of member A of the Read Bay Formation (e.g. Cornwallis Island). There are no significant differences in lithology, fossil content or age between these units, and the name "Douro Formation" should be applied to all three.

The presence of argillaceous divisions and coral-rich zones provides two independent, but complimentary criteria which can be used to correlate sections on southeastern Somerset Island. Coral-rich zones and associated reefs occur in similar stratigraphic positions on Somerset, Cornwallis and Devon Islands. Variation in total shale content between sections makes inter-island recognition of the argillaceous divisions more difficult, but on all three islands the lower part of the formation tends to be more

argillaceous than the upper. The terrigenous content of the rubbly limestones increases regularly in a northeasterly direction; the ultimate source may have been Pearya and/or the Rens Fiord Uplift.

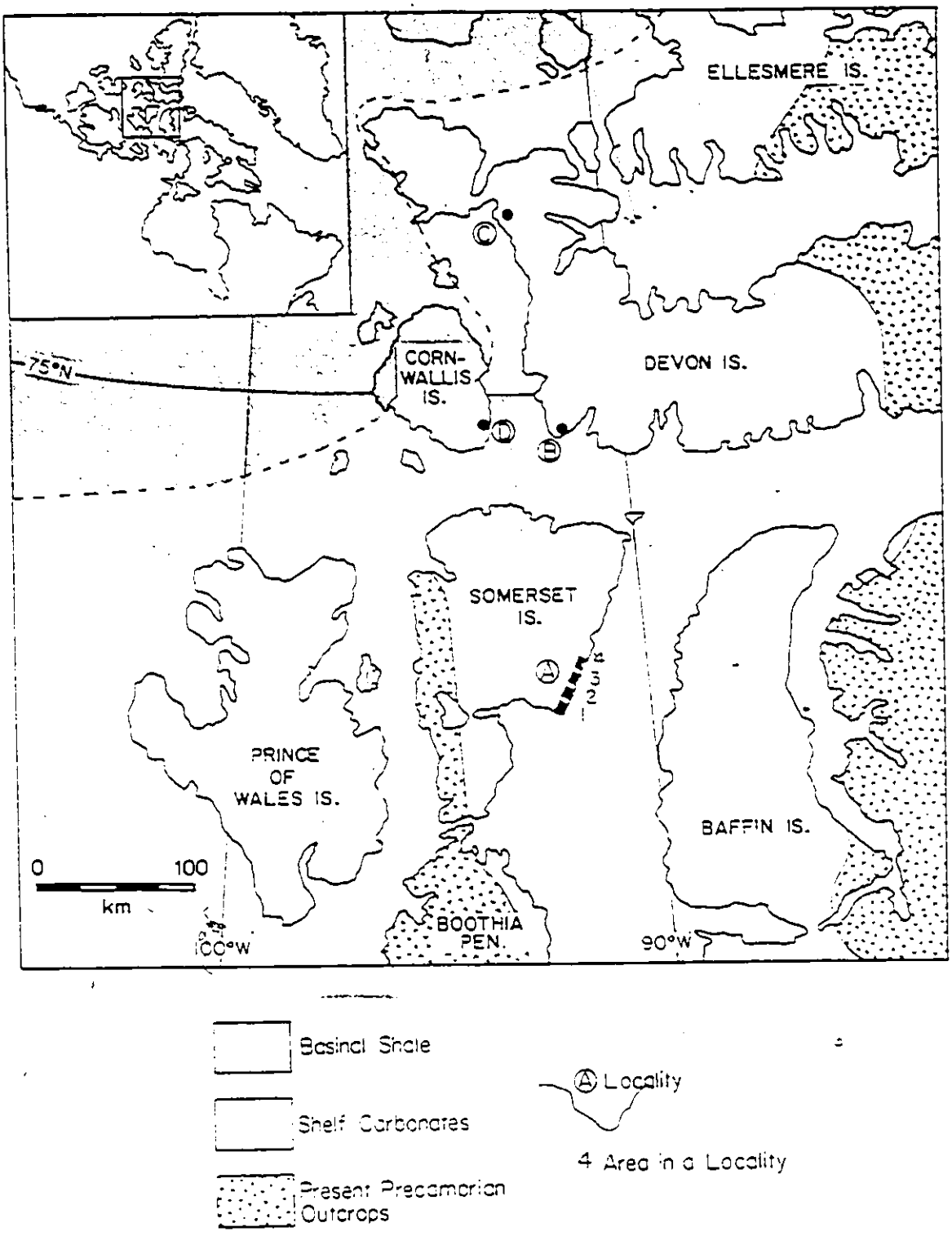
On southeastern Somerset Island, the subtidal strata of the Douro Formation lie conformably between two predominantly intertidal formations. Sponge reefs characterized the two deepest stages of the Douro transgression, whereas oolites and oncolites formed rarely in shallow subtidal environments. The sediments of the Douro Formation probably accumulated mainly in warm, tranquil, turbid waters of normal or near-normal marine salinities.

The Douro Formation is unlikely to contain economic quantities of hydrocarbons, but locally hosts fracture-filling copper deposits.

INTRODUCTION

Rubbly-weathering grey limestones of Late Silurian age occur in corresponding stratigraphic positions on most of the southeastern Canadian Arctic Islands, from southern Ellesmere Island to Boothia Peninsula (Text-fig. 3). Despite their relatively uniform lithologic and paleontologic character over a broad area, three factors have frustrated correlation of these limestones. The first is the uncertainty as to their correct nomenclature. These limestones have been referred to the Read Bay Formation on Boothia Peninsula (Miall and Kerr 1977), Somerset Island (ibid.; Jones and Dixon 1977), Prince of Wales Island (Mayr 1978) and southern Devon Island (ibid.), to member A of the Read Bay Formation on Cornwallis Island (Gibling and Narbonne 1977), and to the Douro Formation on northwestern Devon Island (Morrow and Kerr 1977) and southwestern Ellesmere Island (Kerr 1975). No lithologic criteria have yet been suggested to justify separation of these units, and Thorsteinsson (1963, p. 228), Jones and Dixon (1977, p. 1429), Gibling and Narbonne (1977, p. 1150) and Mayr (1978, p. 23, text-figs. 8, 10) have suggested that they are, at least in part, lithologic equivalents.

Problems in dating have also hindered correlation. Graptolites are present only in a few localities near the platform margin, and hence are not useful for correlation



Text-fig. 3. Location of study sections.

of platformal deposits. Shelly fossils are common in most sections, but very few of the fossil groups have been studied in detail taxonomically. As a consequence, although the shelly fossils suggest a Late Silurian age, they cannot readily be used to distinguish the Ludlovian and Pridolian series (Morrow and Kerr 1977, p. 40; Jones and Dixon 1977, p. 1142). Conodonts are presently more precise age indicators, but they have been studied in relatively few sections.

The extreme scarcity of lithologic marker beds presents the third major problem in correlation. These rubbly limestones are monotonous in character (cf. Miall and Kerr 1977, p. 101), with only minor differences in composition between field units; very few individual units can be traced laterally for more than one kilometre. As a consequence, no consistent internal stratigraphy has yet been proposed for these limestones. This problem is especially critical in areas such as eastern Somerset Island and southwestern Devon Island where complete sections of the rubbly limestone succession are rare.

The present study represents a lithostratigraphic and paleoenvironmental analysis of these Ludlovian rubbly limestones on Somerset, Cornwallis and Devon Islands (Text-fig. 3). The Read Bay Formation was studied at four localities on southeastern Somerset Island and near Radstock Bay on southwestern Devon Island. Member A of the Read Bay

Formation was studied at its type locality on southeastern Cornwallis Island, and the Douro Formation was studied near its type section on northwestern Devon Island.

Sections were divided into field units averaging 1-2 m in thickness. All visible fossils were collected or carefully recorded in the field. At least one large lithic sample was collected from each unit; this was subsequently cut, polished, etched and stained with Alizarin Red-S (cf. Friedman 1959). Thin sections of all major lithotypes were examined.

Detailed logs of all measured sections are on file with the Department of Geology, University of Ottawa. Simplified composite sections are presented in this manuscript.

STRATIGRAPHIC TERMINOLOGY

Previous Work

The Read Bay Formation was defined by Thorsteinsson and Fortier (1954) in their study of the geology of Cornwallis Island. As originally defined, the formation was a relatively thick (>2,600 m) sequence of limestone, dolostone, sandstone and shale which occurred between the underlying dolostones of the Allen Bay Formation and the overlying conglomerates and sandstones of the Snowblind Bay Formation. Thorsteinsson (1958) restricted the formation to the shelly deposits in southern

Cornwallis Island, referring the graptolitic shales to the north to the newly-named Cape Phillips Formation. Thorsteinsson recognized four members within the Read Bay Formation and named them, in ascending order, members A to D. He regarded the formation as predominantly Late Silurian in age.

Regional geologic mapping by the Geological Survey of Canada (Thorsteinsson and Tozer 1962; Fortier et al. 1963; Blackadar and Christie 1963) resulted in recognition of the Read Bay Formation on most of the southern and eastern Canadian Arctic Islands. On Somerset Island, all strata between the Allen Bay and Peel Sound Formations were referred to the Read Bay Formation (Thorsteinsson and Tozer 1963; McMillan 1963; Norris 1963; Blackadar 1963a,b; Blackadar and Christie 1963). Greiner (1963) recognized the undivided Read Bay Formation on southwestern Devon Island. On northwestern Devon Island, Thorsteinsson (1963) named four new formations which he later (in Thorsteinsson and Tozer 1970, p. 559) referred to the Read Bay Group. Thorsteinsson (1963, p. 228) regarded the oldest of these, the Douro Formation, as the lithologic and paleontologic equivalent of member A of the Read Bay Formation.

The Cape Storm Formation was named by Kerr (1975) for a distinctive succession of thinly planar-bedded, predominantly fine-grained dolostones and limestones underlying the Douro

Formation on southwestern Ellesmere Island. The Cape Storm Formation has been recognized throughout the southeastern Canadian Arctic Islands (Kerr 1975). It includes strata formerly assigned to the upper part of the Allen Bay Formation on Devon Island (Kerr 1975), to the lower part of the Read Bay Formation on western Somerset Island (Miall and Kerr 1977) and to the boundary strata of both formations on Cornwallis Island (Thorsteinsson in Kerr 1975).

The Leopold Formation was named by Jones and Dixon (1975) for a unit of thinly planar-bedded, fine-grained dolostone, limestone and sandstone which underlies the Read Bay Formation on eastern Somerset Island. Reinson et al. (1976), Miall and Kerr (1977) and Mayr (1978) regarded the Leopold Formation as an unnecessary synonym of the Cape Storm Formation, but this was disputed by Dixon and Jones (1978) who considered that the two formations could be distinguished by the greater proportion of sandy, evaporitic and stromatolitic units in the Leopold Formation.

On Somerset Island, Miall et al. (1979) defined the Somerset Island Formation for a unit of thinly planar-bedded, fine-grained sandy dolostone, limestone and siltstone. The Somerset Island Formation comprises strata formerly referred to the upper part of the Read Bay Formation and the lower part of the Peel Sound Formation.

Bryozoans throughout the Read Bay Formation at Fury Point on southeastern Somerset Island are Ludlovian in age (Bolton

in Narbonne 1977), a view supported by the presence of the Ludlovian conodont Ozarkadina n. sp. B Klapper (in Klapper and Murphy 1975) in the uppermost strata of the formation (T.T. Uyeno, pers. comm. 1979). Although a few questionable Pridolian dates have been obtained, conodont studies of the Read Bay Formation on northern Somerset Island (Uyeno in Jones and Dixon 1977, pp. 1442-1445), member A of the Read Bay Formation on Cornwallis Island (Uyeno 1977) and the Douro Formation on Devon Island (Uyeno in Morrow and Kerr 1977, p. 122) suggest that all three units are Ludlovian in age.

Recommendations

The recognition of the Cape Storm, Leopold and Somerset Island Formations has resulted in the once heterogeneous Read Bay Formation of Somerset Island being restricted to a homogeneous succession of rubbly limestone. This succession compares closely with the Douro Formation of Devon Island and with the lower half of member A of the Read Bay Formation on Cornwallis Island. All three are of Ludlovian age and overlie the Cape Storm Formation or its sand-rich lateral equivalent, the Leopold Formation. They are similar lithologically, consisting predominantly of nodular and wavy-bedded, argillaceous to dolomitic, fine-grained limestone with interbeds of bioclastic limestone and calcareous shale.

All three contain numerous fossils, especially the smooth-shelled brachiopods Atrypoidea (=Atrypella) and Protathyris (Smith 1976; Jones 1979). There are no marked differences in thickness between the three units.

A common formational name is probably appropriate for these three units. It is here suggested that the name "Douro Formation" be extended throughout Somerset, Cornwallis and Devon Islands to encompass these strata. The Douro Formation could be regarded as one of the formations of the Read Bay Group, as suggested by Thorsteinsson (in Thorsteinsson and Tozer 1970, p. 559) and Kerr (1975, p. 69).

Thorsteinsson (in press) has carried out detailed biostratigraphic studies of all Upper Silurian - Lower Devonian strata in the central Canadian Arctic Islands. In this manuscript, he extended the term "Douro Formation" throughout the southeastern Canadian Arctic Islands and regarded the formation as the basal unit of a revised Read Bay Group. The detailed lithologic correlations proposed in the present study support Thorsteinsson's conclusion, which was based on a broad lithologic similarity and evidence of a Late Ludlovian age throughout the Arctic Islands.

LITHOTYPES

Rubbly Limestone

Rubbly limestone consists of lumps and thin, irregular beds of fine-grained limestone surrounded by a matrix of dolomite and/or shale. Differential weathering of the dense limestone lumps and the softer matrix results in the characteristic rubbly-weathering pattern (Pl. 1). Rubbly limestone occurs rarely in the formations immediately underlying and overlying the Douro Formation, but is most common in the Douro Formation, in which it constitutes more than 80% of the rocks.

The nature and origin of the Douro rubbly limestone have been discussed in detail by Jones et al. (1979). They recognized two main divisions of rubbly limestone: rubbly mottled dolomitic limestone, in which the matrix consists of dolomite; and rubbly argillaceous limestone, in which the matrix contains significant amounts of shale. In the present study, three types of rubbly argillaceous limestone were recognized based on the percentage of shale in the rock. These subdivisions are termed: slightly argillaceous (approximately 10-20% shale), moderately argillaceous (approximately 20-50% shale) and highly argillaceous (>50% shale). Rubbly mottled dolomitic limestone contains less than 10% argillaceous detritus.

Plate 1

Field appearance of the Douro Formation on southeastern Somerset Island.

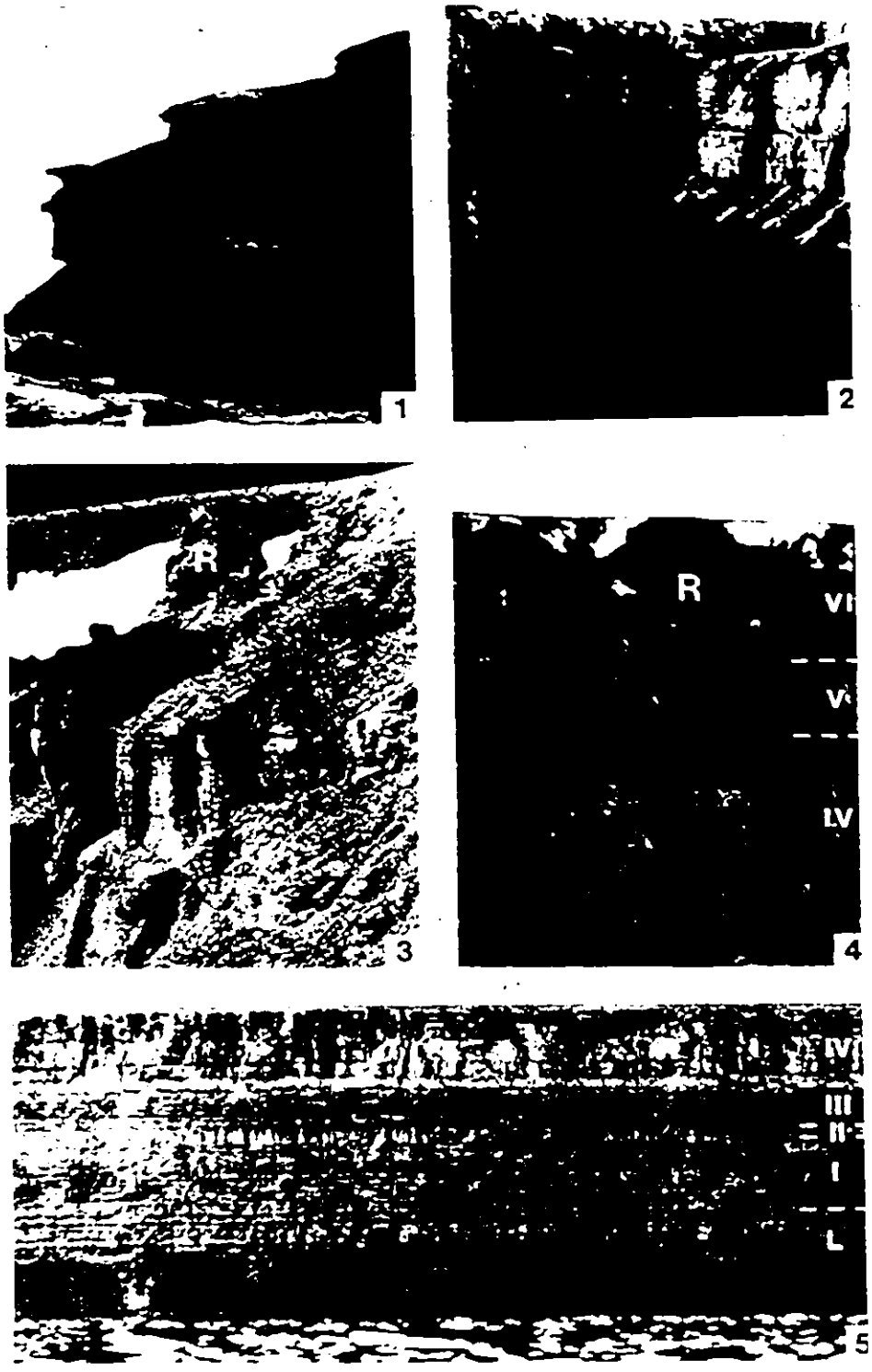
Fig. 1. Moderately argillaceous rubbly limestone (recessive) with interbeds of planar-bedded intraclastic and bioclastic limestone (resistant). Leopold-Douro contact occurs at lower stream level. Approximately 15 m of strata are exposed. Area 4, division I.

Fig. 2. Moderately and slightly argillaceous rubbly limestone. Approximately 150 m of strata are exposed. Area 2, divisions II-VI.

Fig. 3. Rubbly limestone with one small reef (R). Approximately 40 m of strata are exposed. Area 3, divisions I-II.

Fig. 4. Divisions IV-VI with one small reef (R). Approximately 45 m of strata are exposed. Area 2.

Fig. 5. Leopold Formation (L) and divisions I-IV of the Douro Formation. Approximately 150 m of strata are exposed. Area 2.



Pl. 1

The terrigenous component of rubbly limestone consists predominantly of particles of quartz, feldspar, muscovite and clay minerals 1-15 μm in length (Jones et al. 1979, pp. 238-239); units rarely contain coarse silt and very fine sand. The limestone component consists of mudstone or, less commonly, wackestone. Jones et al. (1979) suggested that the lumps formed as a result of synsedimentary lithification below the sediment-water interface. They concluded that the composition of the matrix reflected the rate of influx of detrital sediments and, to a lesser degree, the amount of dolomitization and pressure solution.

Other Lithotypes

Planar-bedded bioclastic and intraclastic limestones (Pl. 1, fig. 1) constitute approximately 15% of the rocks of the Douro Formation. These clastic limestones occur predominantly in lenses and beds less than 0.2 m thick, but locally form units up to 1.5 m thick. Units are erosionally-based, and commonly exhibit graded bedding; planar cross-stratification and megaripples are rare. Bioclastic deposits consist of coarse sand- to pebble-sized fossils, chiefly brachiopods, gastropods and crinoid pleuricolumnals; basal portions of some units contain intraclasts. Intraclastic limestones consist of granule- to pebble-sized, rounded to blade-shaped intraclasts. These bioclastic and intraclastic

limestones probably represent storm-generated deposits (Jones and Dixon 1976).

Small mounds with abundant sponges, corals and stromatoporoids are locally common (Jones and Dixon 1977, p. 1437; Narbonne and Dixon 1978; Part II). These reefal structures (Pl. 1, figs. 3,4) are composed of unbedded mudstone and wackestone; associated lenses, tongues and channel-fills of crinoidal packstone occur in the inter-reefal beds. Reefal deposits constitute 2-3% of the rocks of the Douro Formation on Somerset Island.

Units of medium-bedded mudstone and argillaceous mudstone (calcilutite) occur sporadically throughout the Douro Formation. Many of these units exhibit a labyrinthine pattern of selectively dolomitized burrows. Very thin, planar-bedded units of mudstone (calcisiltite) occur sporadically throughout the lower parts of the formation in most localities. Thin units of planar-bedded oolitic packstone occur very rarely.

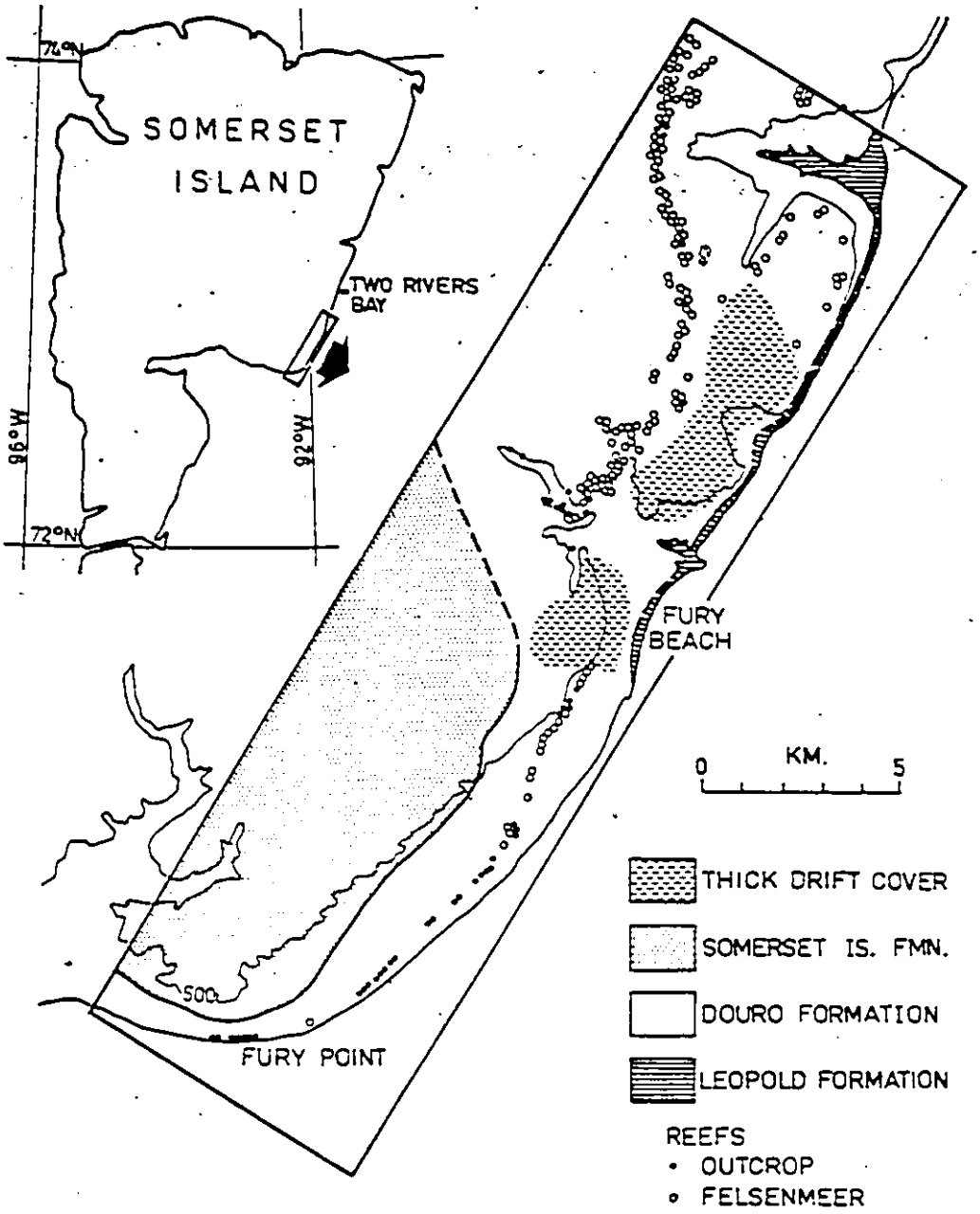
SOUTHEASTERN SOMERSET ISLAND

Areas of Study

On southeastern Somerset Island, the Douro Formation lies conformably between the underlying Leopold Formation and the overlying Somerset Island Formation. The Douro Formation was studied in four areas along the southeast coast (Text-fig. 3). Within each area, two to eight sections 10-160 m thick were measured, and a composite section for the area was produced. In addition, a coastal strip approximately 5 km wide and 30 km long encompassing Areas 1-3 was traversed on foot in order to produce a geologic map (Text-fig. 4).

Lithology

Few individual units could be correlated with any confidence between sections. A unique edgewise conglomerate can be traced virtually continuously throughout and between Areas 1 and 2. The Leopold-Douro contact occurs in Areas 2-4, but the units immediately underlying and overlying the contact differ from section to section. No other individual units or horizons could be traced with certainty between any two areas.



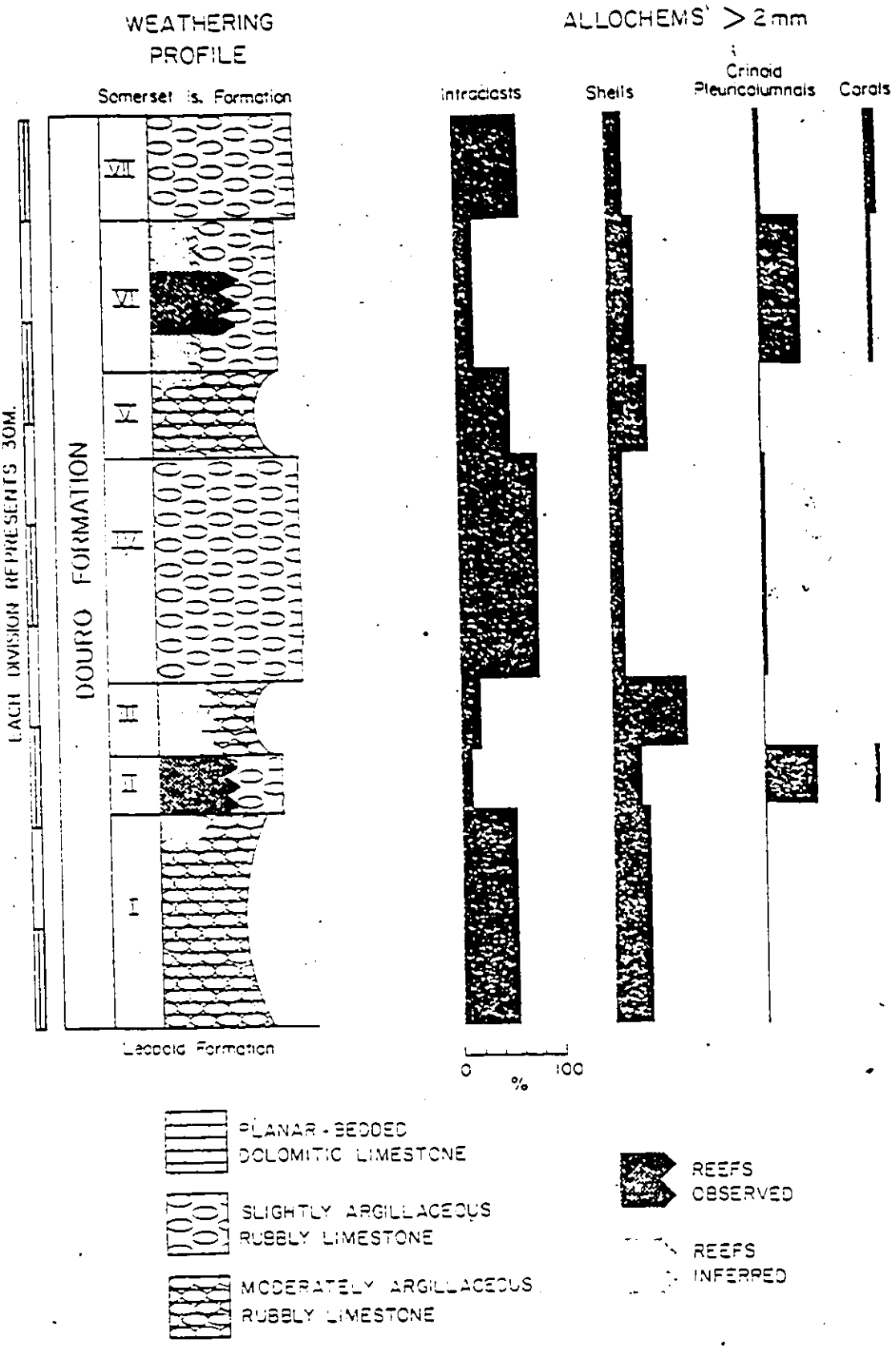
Text-fig. 4. Geologic map of southeastern Somerset Island (Areas 1-3) showing the distribution of reefs of the Upper Reefal Zone. "500" = 500 foot (approx. 150 m) contour.

Nevertheless, consideration of the overall character of the Douro Formation over several tens of metres has resulted in recognition of seven lithologic divisions within the formation (Text-fig. 5). Each division contains a variety of lithotypes, but exhibits an overall lithologic character distinct from all other divisions. Boundaries are gradational over 1-5 m. Although they are readily recognizable in stratigraphic sections, most divisions would be exceedingly difficult to map and hence could not be regarded as members.

Variation in shale content of the rubbly limestone was the principal criterion used to distinguish these divisions. Although individual units within a division exhibit a broad range in shale content, the predominant lithology of each division differs from that of the underlying and overlying divisions. Shale content is best determined through examination of stained hand samples or analyses of insoluble residue content, but can be estimated in the field and is closely reflected in the weathering profile (Pl. 1, figs. 2-5).

Divisions I, III and V consist predominantly of moderately argillaceous rubbly limestone (20-50% terrigenous detritus) whereas divisions II, IV, VI and VII consist predominantly of slightly argillaceous rubbly limestone (10-20% terrigenous detritus). Terrigenous detritus of divisions II-VII is almost entirely mud-sized, but division I contains minor amounts of coarse silt and very fine sand.

Text-fig. 5. Profile of the Douro Formation on southeastern Somerset Island showing predominant lithology, stratigraphic position of reefs and composition of the clastic limestones. I-VII designate the lithologic divisions of the formation. Section and data on allochem composition are a composite of Areas 1 and 4.

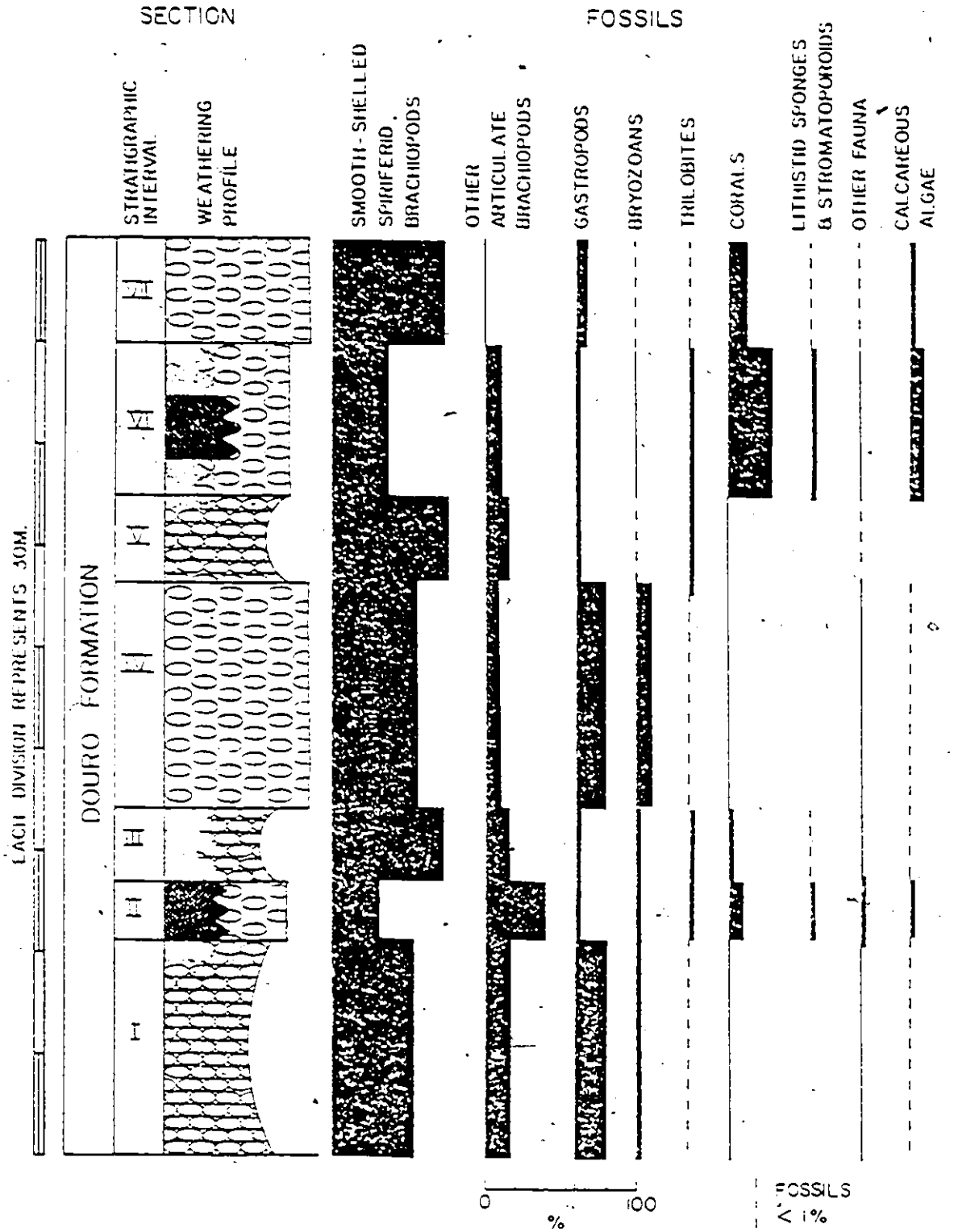

WEATHERING PROFILE
Somerset Is. Formation
DOURO FORMATION
Lecpold Formation
EACH DIVISION REPRESENTS 30M.
VII
VI
V
IV
III
II
I
ALLOCHEMS > 2 mm
Intraclasts
Shells
Crinoid Pleuncolumnals
Corals
0
100
%
PLANAR-BEDDED DOLOMITIC LIMESTONE
SLIGHTLY ARGILLACEOUS RUBBLY LIMESTONE
MODERATELY ARGILLACEOUS RUBBLY LIMESTONE
REEFS OBSERVED
REEFS INFERRED

Allochem composition also varies from one division to another (Text-fig. 5). Intraclasts constitute more than 50% of allochems greater than 2 mm in divisions I, IV and VII. Intraclasts and fossil debris are approximately equal in proportion in division V, and fossil debris predominates in divisions II, III and VI. Disarticulated crinoid pleuricolumnals occur throughout the formation, but form a significant portion of the fossil debris only in divisions II and VI.

Fossil Content

The fossil content of the seven divisions is shown diagrammatically in text-figure 6. Fossils are common in the Douro Formation, locally constituting several per cent of the rock, and hence can be regarded as both lithologic and paleontologic features. Approximately 9,000 *in situ* fossils were collected from the Douro Formation of south-eastern Somerset Island during this study.

Brachiopods constitute 50-95% of the fauna (by number) of each division. Most of the brachiopods are specimens of the smooth-shelled spiriferids *Atrypoidea* and *Protathyris* (Pl. 2, figs. 1,2) which together form almost 70% of the total fauna. Gastropods, chiefly murchisonids (Pl. 2, fig. 2) occur throughout the formation, but are most common in divisions I and IV. Significant numbers of corals occur



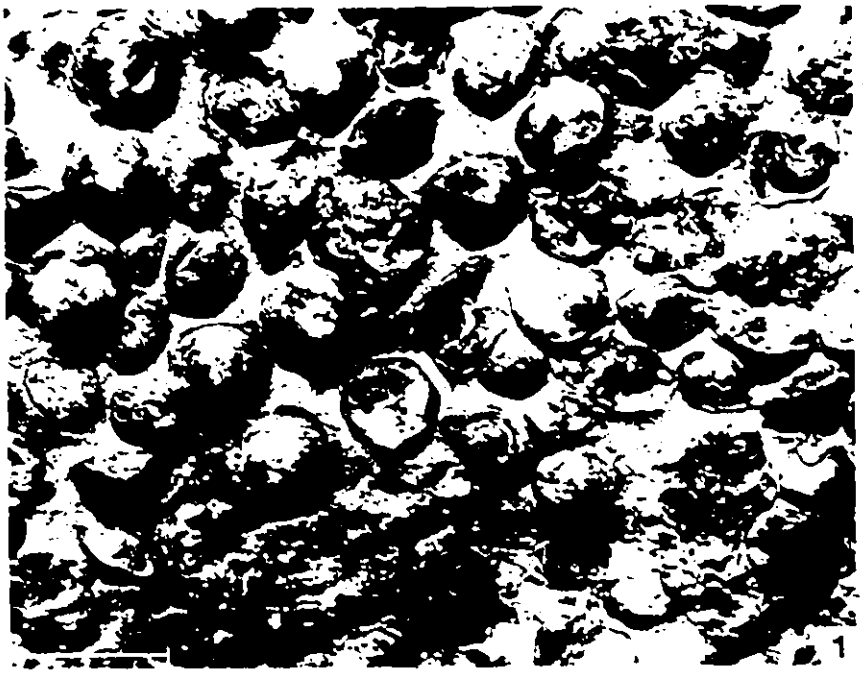
Text-fig. 6. Fossil composition of the Douro Formation on southeastern Somerset Island. Section a composite of Areas 1-4; fossil data combined from all sections. Lithologic symbols are the same as those in text-fig. 5.

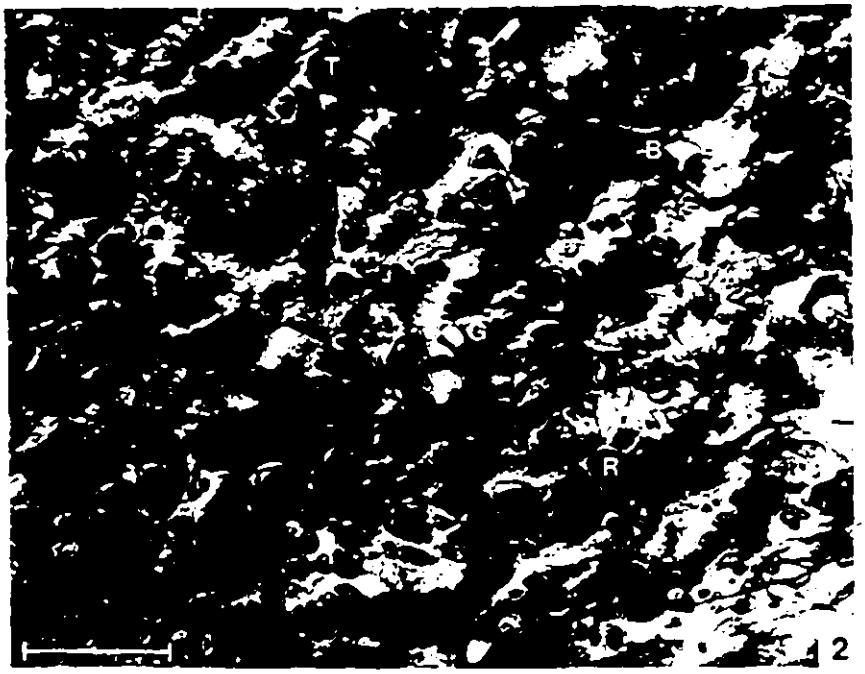
Plate 2

Upper surfaces of fossiliferous slabs of the Douro Formation. Area 2, division IV. Scale bar represents 2 cm.

Fig. 1. Numerous specimens of the brachiopod Atrypoidea (= Atrypella).

Fig. 2. Specimens of Atrypoidea (A), rhynchonellid brachiopods (R), gastropods (G), bryozoans (B) and trilobites (T).





Pl. 2

in divisions II, VI and VII. The presence of coral faunas is readily recognizable in the field, and thus forms an additional criterion for the recognition of divisions.

The presence of reefs provides an independent, but supplementary criterion for subdivision of the Douro Formation. Reefs occurred commonly within measured sections. In addition their occurrence within a division could be inferred from the presence of: 1) typical reef-derived deposits such as channels filled with crinoidal packstone, 2) transported reef blocks or reef-derived fossils in crinoidal deposits, or 3) reefs exposed in strata laterally equivalent to a measured section.

Reefs occur in two stratigraphically-separated zones within the Douro Formation (Text-figs. 5,6). Differences in faunal composition allow the two reefal zones to be readily distinguished (Part II). Reefs of the lower zone occur rarely in division II, and are inferred to occur throughout division III and in the uppermost 5 m of division I. Reefs of the upper zone occur rarely to commonly throughout division VI and are inferred to occur very rarely in the uppermost 5 m of division V. Within the mapped area (Areas 1-3), 3 reefs of the lower zone and more than 200 reefs of the upper zone were observed in outcrop and in undisturbed felsenmeer. Within this area, the distribution of reefs of the upper zone is readily mappable (Text-fig. 4).

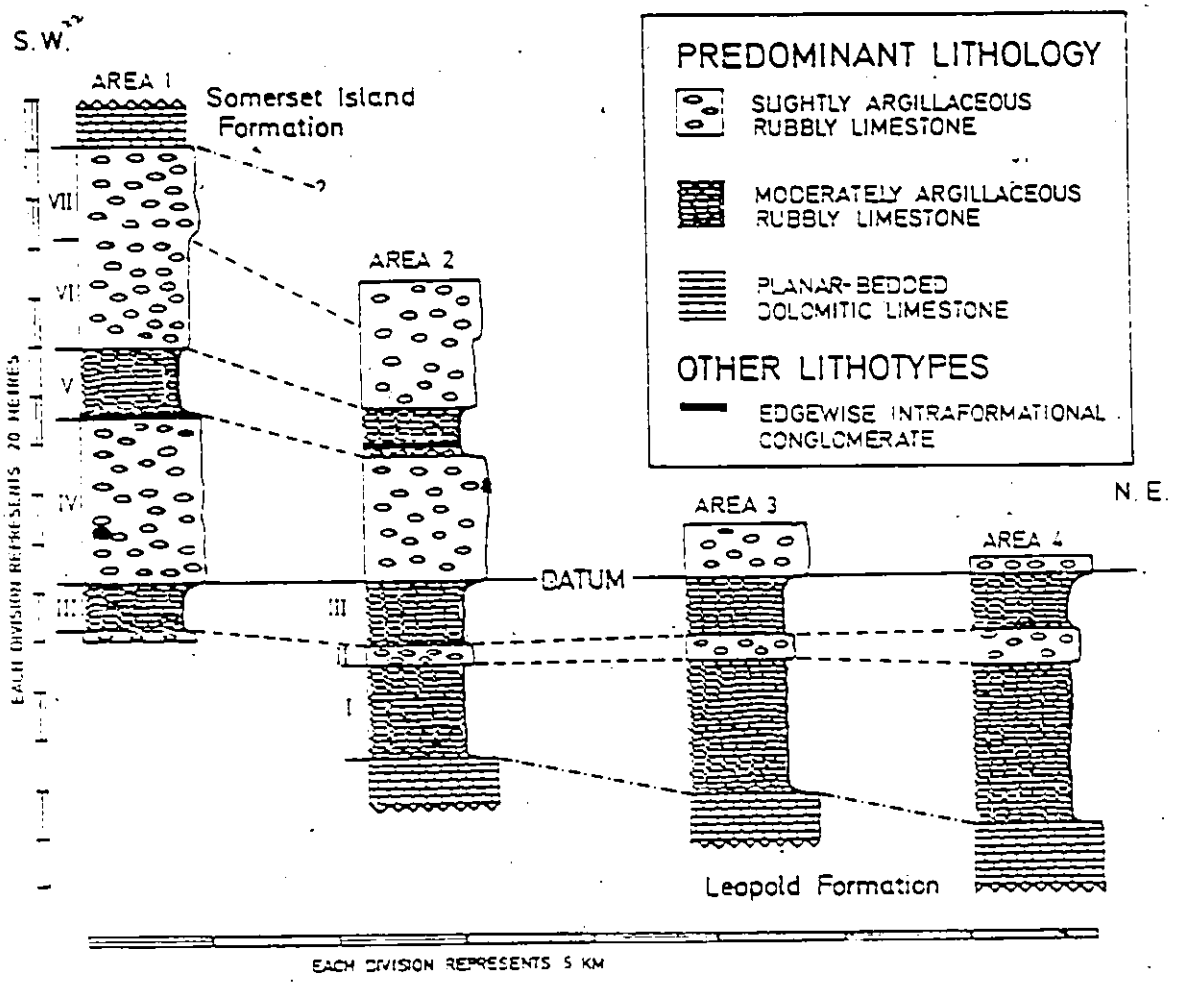
Local Correlation

Lithologic correlation of the four composite sections is illustrated in text-figure 7, using the top of division III as a datum. The boundary between divisions III and IV is relatively sharp, and can be readily recognized in all four sections.

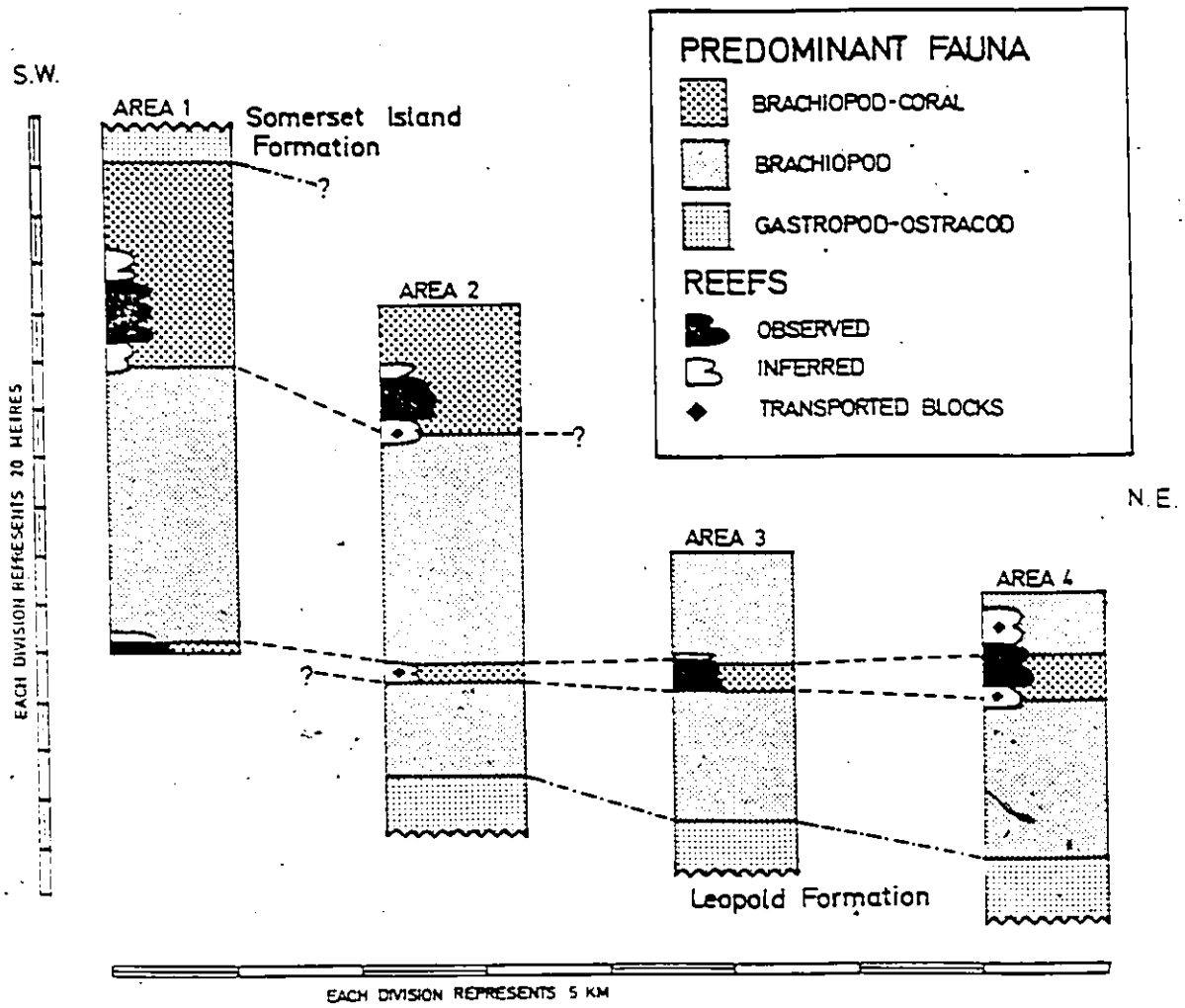
None of the divisions pinch out within the area of study (40 km). Divisions commonly vary in thickness between sections, but an apparent northeastwards thickening of divisions I and II was the only definite trend noted. Division IV apparently thins between Areas 1 and 2, but insufficient data are available to determine whether this is part of a general trend.

Correlation based on predominant fauna yields complementary, but less refined results (Text-fig. 8). A northeastwards thickening of the two lower faunal zones of the Douro Formation corresponds to the thickening of divisions I and II. The Lower Reefal Zone also apparently thickens in the same direction.

Correlation of the composite sections suggests that the Douro Formation on southeastern Somerset Island is 225-275 m thick.



Text-fig. 7. Correlation of the Douro Formation on southeastern Somerset Island using predominant lithology.



Text-fig. 8. Correlation of the Douro Formation on south-eastern Somerset Island using predominant fauna.

Depositional Environments

Paleomagnetic evidence (Irving 1979; Scotese et al. 1979) suggests that the Late Silurian position of southeastern Somerset Island was 10-20° north of the equator. This would suggest a warm climate, a view supported by the faunal and floral composition (Text-fig. 6). The sediments of the Douro Formation accumulated on a broad carbonate shelf, approximately 250 km south of the shelf margin (Text-fig. 3).

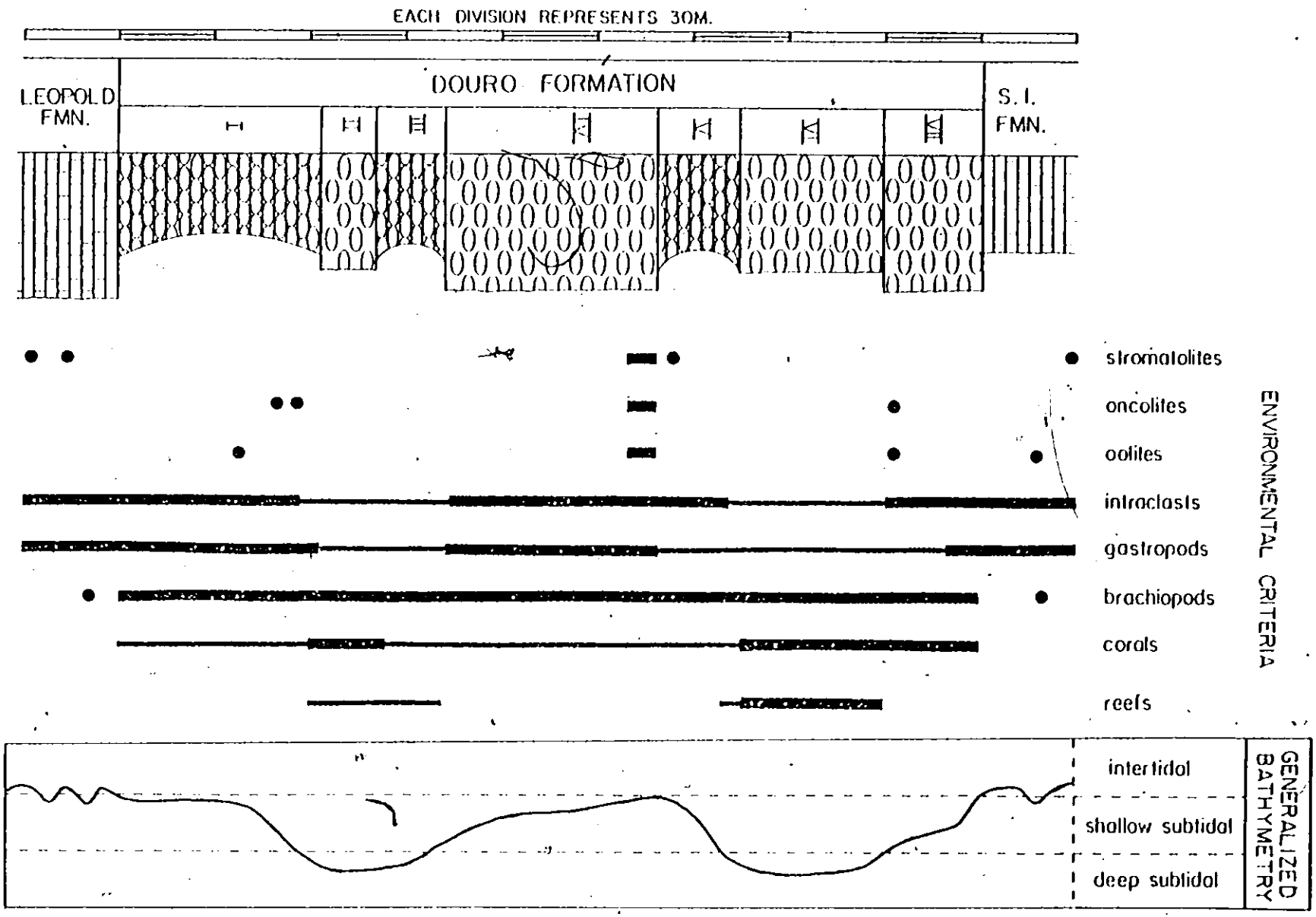
The fauna and flora of the Douro Formation overwhelmingly suggest a subtidal shelf environment of normal to slightly elevated salinity (cf. Heckel 1972, text-figs. 3, 4), a view also supported by geochemical evidence (Veizer et al. 1978). The occurrence of large numbers of Atrypoidea suggests somewhat turbid conditions (Jones 1979, pp. 408-409). The very fine grain-size and scarcity of current indicators in the rubbly limestone is typical of relatively low energy deposits. Most fossils of sedentary benthic organisms are still in life position, and the majority of the brachiopods are still articulated. These features suggest that most of the formation accumulated in relatively calm environments with only minor turbulence. However, interbeds of storm-deposited bioclastic and intraclastic limestone suggest that deposition occurred above storm wave-base.

The subtidal Douro Formation lies conformably between two predominantly intertidal formations (Dixon and Jones 1978; Miall et al. 1978; Miall and Gibling 1978). The Douro therefore

may show features representing progressive changes in bathymetry and water turbulence.

Subtidal carbonates of epeiric seas can be divided into shallow subtidal deposits, which show evidence of intermittent to continuous wave action, and deep subtidal deposits, which do not (Laporte 1971). Relative proportions of rubbly limestone and clastic limestone, the two major lithotypes, do not vary significantly from one division to another and hence cannot be used as paleoenvironmental indicators. However, the composition of the clastic limestone varies considerably among the divisions (Text-fig. 5). Jones and Dixon (1976, pp. 395-396) concluded that the Douro intraclastic limestones represented higher energy regimes than the bioclastic limestones. On southeastern Somerset Island, intraclasts constitute more than 50% of clasts greater than 2 mm in divisions I, IV, V and VII; in other divisions shells and/or crinoid pleuricolumnals predominate. The intraclast-rich deposits probably accumulated in more turbulent, presumably shallower environments than did the shell-rich deposits. Ripple-marks and megaripples occur most commonly in intervals I, IV and VII; oolites and oncolites, considered indicative of shallow subtidal environments (Laporte 1971, Table 1), were observed only in these three divisions. Low amplitude, colloform stromatolites occur rarely in division IV and the base of division V, further suggesting a shallow subtidal environment for these deposits (cf. Hoffman 1976).

Text-fig. 9. Paleoenvironmental interpretation of the Douro Formation on southeastern Somerset Island. Usage of "shallow subtidal" and "deep subtidal" as in Laporte (1971). Lithologic symbols are the same as those in text-fig. 5.


EACH DIVISION REPRESENTS 30M.
LEOPOLD FMN.
DOURO FORMATION
S. I. FMN.
stromatolites
oncolites
oolites
intraclasts
gastropods
brachiopods
corals
reefs
ENVIRONMENTAL CRITERIA
intertidal
shallow subtidal
deep subtidal
GENERALIZED BATHYMETRY
COMMON
RARE
SINGLE OCCURRENCE

The reefs of this study consist of lime mudstone and wackestone baffled by thin-walled lithistid sponges. These reefs could not have withstood the force of breaking waves, and probably formed in calm environments well below wave-base (Part II).

A generalized bathymetric curve for the Douro Formation on southeastern Somerset Island is presented in text-figure 9. According to this model, reef growth occurred during the two deepest stages of Douro transgression (primarily represented by divisions II, III and VI), whereas intraclasts, oolites, oncolites and stromatolites were common only in shallower environments (primarily represented by divisions I, IV, V and VII).

Within the study area, articulate brachiopods occurred abundantly in subtidal shelf environments but were very rare in the intertidal zone. Gastropods occurred in all bathymetric zones but were most common in intertidal and shallow subtidal environments. Corals occurred sporadically throughout the subtidal zone but were most common in the deep subtidal, especially in association with reefs. Corals were also common in shallow subtidal environments at the close of the deposition of the formation, but diversity was less than 20% that of the deep subtidal. Trilobites, lithistid sponges, stromatoporoids and calcareous algae (Pseudochaetetes) were also most common in

deep subtidal environments, particularly in association with reefs. However, most of the changes in faunal and floral composition throughout the Douro Formation were relatively minor and commonly inconsistent, suggesting that differences in bathymetry and water energy were not pronounced.

The amount of argillaceous detritus in the rubbly limestones was apparently largely independent of bathymetry (Text-fig. 9). More likely, it was primarily controlled by changes in the source area and in distribution patterns.

REGIONAL COMPARISONS

Location of Sections

Complete sections of the Douro Formation were measured at three localities on Cornwallis and Devon Islands (Text-fig. 3). In addition, comparisons were made with complete sections measured at Pressure Point on northwestern Somerset Island (Jones 1974; Jones and Dixon 1977; Jones et al. 1979; O.A. Dixon, pers. comm. 1980), and near Cape Garry and in the West Creswell River area on southwestern Somerset Island (Savelle 1978).

The Douro section on Cornwallis Island was measured along Goodsir Creek, type section for member A of the Read Bay

Formation (Thorsteinsson 1958, pp. 48-54). At this locality, member A overlies the Cape Storm Formation and is overlain by the shales of the lower member of the Barlow Inlet Formation (formerly member B of the Read Bay Formation). The depositional environments of these strata have been discussed by Gibling and Narbonne (1977, pp. 1148-1149) and Thomas and Narbonne (1979, pp. 3-4).

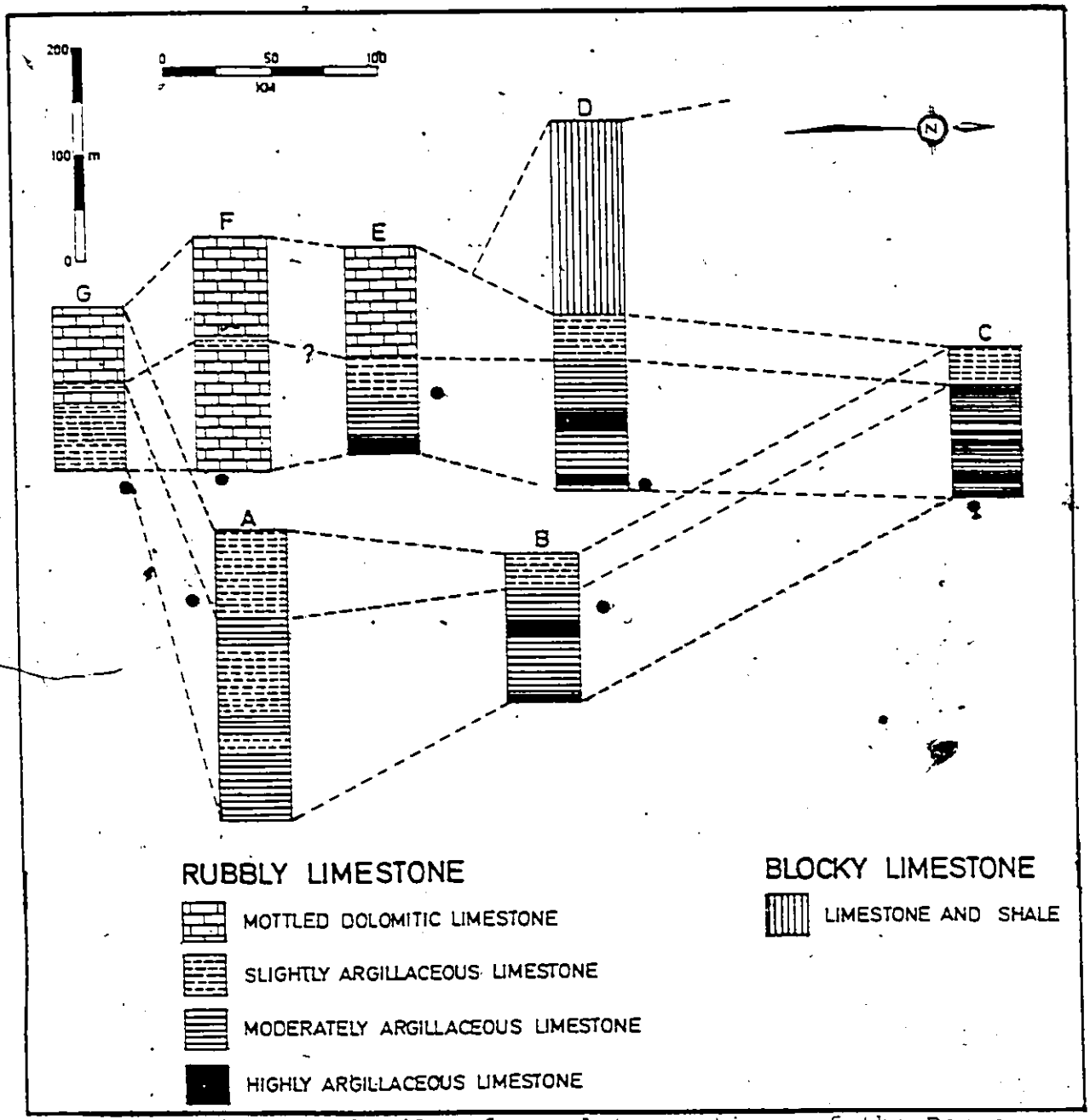
A section was measured along the south bank of Sutherland River in the Douro Range of northwestern Devon Island (section 4 of Morrow and Kerr 1977). Due to inclement weather, it was not possible to measure the actual type section of the Douro Formation, but the section along the Sutherland River is considerably better exposed and is situated only 4 km to the south. On northwestern Devon Island, the Douro Formation is underlain by the Cape Storm Formation and overlain by the Devon Island Formation. The depositional environments of the Douro Formation in this area have been discussed by Morrow and Kerr (1977, p. 46).[1]

[1] Morrow and Kerr (1977, pp. 91-92, text-fig. 21) measured approximately 95 m of Douro Formation at this locality, the thinnest complete section measured anywhere in the Arctic Islands (Thorsteinsson, in press). Remeasurement by the author yielded a thickness of approximately 140 m; this is closely comparable to the thickness of the Douro Formation in two nearby sections measured by Morrow and Kerr (1977, text-fig. 21, Sections 3 and 7), and to the thickness measured by the author on southwestern Devon Island.

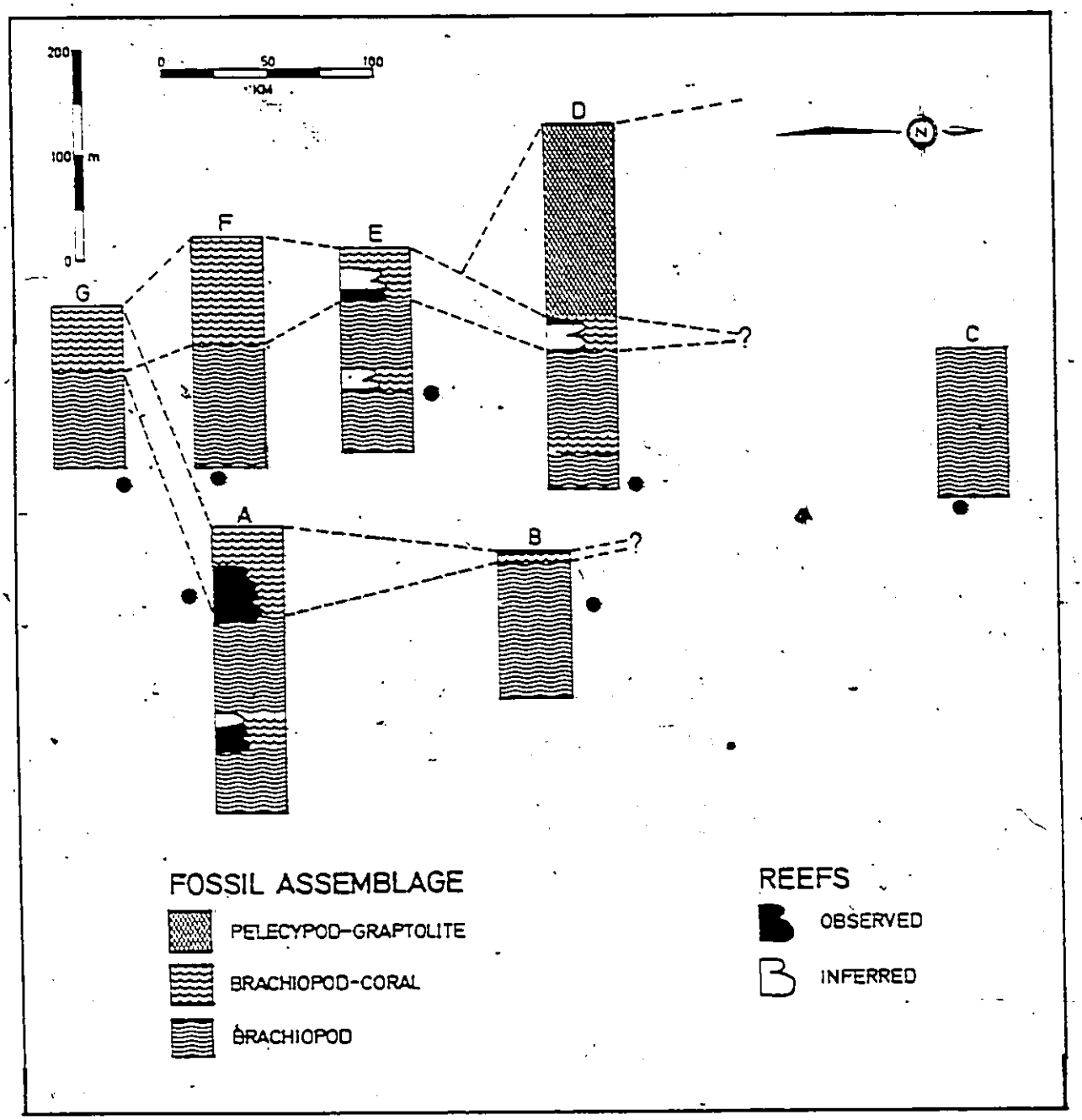
A composite section of the Douro Formation was measured at Dealy Point and Gascoyne Inlet on southwestern Devon Island. A summary of this section is presented in this paper; details will be published later by R. Thorsteinsson and U. Mayr (in preparation). The Douro Formation on southwestern Devon Island is underlain by the Cape Storm Formation and overlain by member C of the Read Bay Formation. Depositional environments have been discussed by Mayr (1978, p. 22).

Regional Correlation

Lithostratigraphic correlation of the seven composite sections is illustrated in text-figures 10 and 11. Although the sections span a distance of more than 600 km, they are remarkably similar lithologically. All seven are composed predominantly of rubbly limestone with thin interbeds of bioclastic and intraclastic limestone; the only significant differences between the sections are in the shale content of the rubbly limestones. Similarly, the fauna of the seven sections is dominated by smooth-shelled brachiopods with some zones rich in corals. This strong lithologic and paleontologic similarity over a broad area strongly suggests that a common formational name is appropriate for these strata.



Text-fig. 10. Correlation of complete sections of the Douro Formation in the southeastern Canadian Arctic Islands using predominant lithology. The lowest and highest lines mark the contacts with underlying and overlying units, and the middle-line marks the top of the more argillaceous lower part of the formation. Blocky limestone in the upper half of section D represents a tongue of the ?Cape Phillips Formation.



Text-fig. 11. Correlation of complete sections of the Douro Formation in the southeastern Canadian Arctic Islands using predominant fauna. Lines show the correlation of the upper coral-rich zone. Note that a lower coral-rich zone can be recognized in localities A, D and E. The pelecypod-graptolite assemblage occurs in a tongue of the ?Cape Phillips Formation.

The only exception noted is the upper half of the section at Goodsir Creek, Cornwallis Island. These strata are blocky-weathering, planar-bedded lime mudstone and shale; bioclastic units are very rare and intraclastic units were not observed. Monograptids (Bohemograptus) and bivalves (Cardiola) are predominant in the sparse fauna. These strata represent a tongue of basinal deposits extending to the south (Gibling and Narbonne 1977, p. 1149; Mayr 1978, p. 23; Thomas and Narbonne 1979, p. 3). They were originally included in member A of the Read Bay Formation (Thorsteinsson 1958) and are probably equivalent in age to the upper part of the Douro Formation elsewhere in the Arctic Islands (Mayr 1978; Thorsteinsson, in press). However, they differ significantly in lithology, paleontology and weathering character from the Douro Formation at its type locality and throughout the Arctic Islands. They should probably be regarded as a tongue of the Devon Island Formation (Mayr 1978) or the Cape Phillips Formation (Thomas and Narbonne 1979), but should not be included within the revised Douro Formation.

Equivalents of several of the stratigraphic divisions present on southeastern Somerset Island can be recognized on northwestern Somerset Island and southeastern Cornwallis

Island (Text-fig. 10). However, none of the divisions can be recognized in all sections, and variation in total shale content hinders recognition of these divisions even on Somerset Island. For these reasons, it is necessary to use larger and more distinctive stratigraphic intervals for lithologic correlation between the islands.

Jones and Dixon (1977, p. 1445) noted that the lower part of the Douro Formation on northwestern Somerset Island is more argillaceous than the upper part. This generalization appears to be true for the Douro Formation on all three islands. The total amount of shale varies from one section to another, but generally the upper part of the formation contains less shale than the lower part (Text-fig. 10). Minor amounts of very fine sand are present in the uppermost strata of the Douro Formation at some localities on Somerset Island (Savelle 1978) and Prince of Wales Island (Miall et al. 1978, p. 185); this minor incongruity is probably related to the initial Late Ludlovian movements of the Boothia Horst.

Jones and Dixon (1977, p. 1445) concluded that, on Somerset Island, brachiopods predominate in the lower part of the Douro Formation whereas corals predominate in the upper part. This is an oversimplification, as a coral-rich zone

is now known to occur in the lower part of the formation at several localities (Text-fig. 11). However, the upper coral-rich zone is thicker and more widespread; it was recognized in all the sections except the one on northwestern Devon Island. The percentage of the total thickness of the Douro Formation represented by the upper coral-rich zone decreases in a northerly direction.

The regression during the middle of Douro Formation deposition (Text-fig. 9) can be recognized in sections throughout Somerset Island. Near the Boothia Horst on southwestern Somerset Island, it was associated with deposition of minor amounts of very fine sand (Savelle 1978, p. 35). However, evidence of this regression was not recognized in sections on Cornwallis or Devon Islands. Most likely, it was local, and perhaps resulted from minor movements of the Boothia Horst.

Thickness Variations

The thickest measured section of the Douro Formation is on Griffith Island to the north of Pressure Point, where the formation is approximately 400-460 m thick (Thorsteinsson, in press; J. Packard, pers. comm. 1980). The thinnest measured sections are on western Devon Island, where several sections approximately 140 m thick are present (Morrow and Kerr 1977; this study). Miall and Kerr (1977, p. 101) noted a general

northward thickening of the formation on Somerset Island and Boothia Peninsula, but insufficient data are presently available to discern any other consistent thickness variations.

Origin and Transport of Terrigenous Detritus

Coarse silt and very fine sand form a significant part of the terrigenous detritus near the base of the Douro Formation in many localities. This detritus was probably derived from the same source as the detritus in the underlying Leopold or Cape Storm Formations, most likely the Precambrian crystalline and sedimentary rocks presently exposed on the eastern margin of the Arctic Archipelago (Dixon et al., in press). Minor amounts of coarse silt-very fine sand in the middle and uppermost strata of the Douro Formation on southwestern Somerset Island may have been derived from minor erosion of sedimentary cover on the Boothia Horst.

However, the distribution of terrigenous detritus in rubbly limestones throughout the study area (Text-fig. 10) strongly suggests that neither of these was an important source for most of the mud-sized detritus in these rocks. The mud content increases regularly to the northeast, suggesting that the source of the detritals lay in this direction. On central Cornwallis and southern Ellesmere Islands, platformal limestone of the Douro Formation passes into basinal shale, siltstone, and limestone of the Cape Phillips Formation

(Thorsteinsson 1958; Kerr 1976). During the Ludlovian, the clastic sediments of the Cape Phillips Formation were derived primarily from the north, most likely from Pearya and/or the Rens Fiord Uplift on the northwestern margin of the Arctic Archipelago (Trettin 1979). These areas presumably formed the source of most of the fine terrigenous detritus in the Douro Formation as well.

A northerly source area implies that this fine-grained terrigenous detritus was transported south across the Hazen Trough and the basin before finally settling out on the shelf. The precise mechanism of transport is presently unknown, but it is possible that the fine clastics were transported in surface turbid layers. Sediment-laden waters may form surface layers if they are markedly warmer or less saline than the underlying waters; flow within this layer (hypopycnal plane jet flow) can transport mud hundreds of kilometres across a basin (Blatt and Totten 1980). The absence of large reefs, islands or shoals along the Douro shelf margin would have allowed surface turbid waters to spread over much of the shelf as well. However, transportation of detritus may have been locally impeded by the shoaling effects of the Boothia Horst.

This mechanism of transport would imply a relatively turbid sea, a view supported by paleontologic evidence (see "Depositional Environments" above).

ECONOMIC POTENTIAL

Within the study area, the rubbly and reefal limestones of the Douro Formation are dense, with negligible permeability and porosity. Bioclastic units are commonly more porous, but are too thin to hold large quantities of oil or gas. These factors, together with apparent absence of bitumen stains and petroliferous odours, suggest that the platformal limestones of the Douro Formation are unlikely to hold economic quantities of hydrocarbons. The transition between the Douro Formation and the basinal Cape Phillips Shale is a more likely prospect, but where this transition is exposed at Goodsir Creek (Area D) large reefs, oolite shoals and other potential reservoirs are not present.

Copper minerals, chiefly bornite, malachite and azurite, fill fractures within the Douro Formation north of Creswell Bay (Savelle 1978, p. 24) and on Griffith Island (J. Packard, pers. comm., 1980). The origin and economic potential of these deposits is presently unknown.

CONCLUSIONS

1. Rubbly-weathering grey limestones of Ludlovian (Late Silurian) age occur in corresponding stratigraphic positions on most of the southeastern Canadian Arctic Islands. They have previously been referred to the undivided Read Bay Formation (e.g. Somerset Island, southern Devon Island), to member A of the Read Bay Formation (southern Cornwallis Island) or to the Douro Formation (northern Devon Island). These three units are closely similar in both lithology and fossil content, and should be regarded as a single widespread unit, the Douro Formation.

2. The relatively monotonous lithologic and paleontologic character of the Douro Formation hinders internal stratigraphy and correlation. Nevertheless, variation in the shale content of the rubbly limestones and in the allochem composition of the clastic limestones permit recognition of seven stratigraphic divisions; these divisions can be correlated along the southeast coast of Somerset Island. Coral-rich zones and related reefal zones provide an independent, but supplementary, criterion for correlation.

3. The Douro Formation on southeastern Somerset Island was deposited on a subtidal platform, probably in warm, turbid, predominantly tranquil waters of normal or near-normal marine salinity. Relatively shallow subtidal deposits contain abundant intraclasts and rare oolites, oncolites, stromatolites and megaripples. Deeper subtidal deposits lack these features, but contain sponge reefs and greater fossil diversity.

4. Two features can be used to correlate sections of the Douro Formation on Somerset, Cornwallis and Devon Islands. Although the total amount of shale varies between sections, the lower part of the formation tends to be more argillaceous than the upper part. In addition, coral-rich zones occur in corresponding stratigraphic positions in most sections.

5. The amount of terrigenous detritus in the Douro Formation increases regularly to the northeast, suggesting that the source area lay in this direction. The mud-sized detritus was probably carried in suspension across the Hazen Trough and basin, finally settling out on the platform.

6. The Douro Formation is unlikely to contain economic quantities of hydrocarbons, but locally hosts fracture-filling copper deposits.

PART II

UPPER SILURIAN LITHISTID SPONGE REEFS ON SOMERSET ISLAND, ARCTIC CANADA

UPPER SILURIAN LITHISTID SPONGE REEFS ON SOMERSET ISLAND, ARCTIC CANADA

Abstract. The Upper Silurian (Ludlovian) Douro Formation on Somerset Island, Arctic Canada contains the first reported Silurian sponge reefs. The Douro Sponge Reefs range from 5 to 35 m in diameter and are composed of unbedded, richly fossiliferous mudstone and wackestone. Fossils, chiefly lithistid sponges, constitute approximately 50% of the reef; geopetally-filled cavities up to 15 cm in length are common.

Reef growth occurred on a broad carbonate platform, probably in warm, tranquil, turbid waters of normal or near-normal marine salinities. Periodic deposition of large quantities of terrigenous mud adversely affected reefal size, and resulted in changes in their biotic composition.

Three distinct stages of reef growth can be recognized. Abundant crinoids and local concentrations of trepostomate bryozoans, solenoporid algae and rhynchonellid brachiopods stabilized and accentuated a loose pile of bioclastic debris (Crinoid Stage). This lens was colonized by lithistid sponges which baffled lime mud to produce a low mound (Sponge Stage). With continued growth of the mound, the sponge

community was gradually replaced by numerous corals and fewer sponges, calcareous algae, bryozoans and stromatoporoids on a substrate of bioclast-rich lime mud (Coral Stage). Diversity of skeletal organisms increased throughout the stages of reefal development. Topographic relief increased from a few decimetres in the Crinoid Stage to about 3 metres in the Coral Stage. During the Sponge and Coral Stages, the reef was surrounded by an irregular apron of bioclastic debris. The abundance and diversity of all skeletal groups, as well as the proportion and average size of the bioclasts, decreased regularly with distance from the reef. Reefs only rarely exerted a significant influence on sediments more than 15 m from their margins.

Much of the reefal lime mud was transported from inter-reefal areas, but significant quantities were produced on the reefs. Cavities which were enlarged by boring organisms and blocks of reefal mudstone which were dislodged and transported by storm waves suggest that the reefs underwent synsedimentary cementation. Three generations of sparry calcite cement in cavities precipitated from meteoric waters.

The originally siliceous spicules of the lithistid sponges have been dissolved and the voids later infilled with sparry calcite. Pervasive formation of interspicular micrite apparently played an important role in the preservation of the

sponges. Early dissolution of siliceous spicules is common in reefal environments, and may have resulted in sponges being under-represented as fossils in ancient reefs.

During geologic periods in which corals were in evolutionary decline (e.g. Early-Middle Ordovician, Late Paleozoic), sponge reefs were common and environmentally widespread; sponges commonly played significant constructional roles in all stages of reefal development, including climax stages. In contrast, sponge reefs were rare and environmentally restricted during periods in which coral faunas were diverse (e.g. Siluro-Devonian, Jurassic, Late Cenozoic); sponges in these reefs commonly occurred as colonization communities which were later replaced by coral-rich climax communities.

INTRODUCTION

Sponges are common elements in modern reefs. Boring demosponges (chiefly clionids and adociids) play a major role in shaping reefs by reducing lithified carbonates and coral skeletons to silt-sized sediment (Goreau and Hartman 1963; Bromley 1978). Large, massive sclerosponges contribute to the framework of deep forereefs (Hartman 1977), and smaller sclerosponges and demosponges strengthen cavity walls and bind

corals together (Hartman 1977; Wulff and Buss 1979). Demosponges are the principal frame builders of small mounds which occur locally on the Great Bahama Bank (Bliefnick and Gebelein 1978; Wiedenmayer 1978, 1980d). However, most reefal sponges are apparently accessory organisms dwelling in deep or sheltered areas (Vacelet and Vasseur 1977), and contributing little to reefal construction.

Although sponges played major constructional roles in some Ordovician, Pennsylvanian, Permian, Triassic and Jurassic reefs (Rigby 1971), they were relatively unimportant in most Silurian and Devonian reefs. The Siluro-Devonian was characterized by extensive development of coral-stromatoporoid reefs. Sponges occurred rarely in these structures, generally as reef dwellers living in deep or sheltered areas (e.g. Lowenstam 1957; Manten 1971; Rigby 1979). Sponge reefs have not been previously reported from Silurian or Devonian strata.

The Upper Silurian Douro Formation on Somerset Island in the Canadian Arctic Archipelago contains the first reported Silurian sponge reefs. Their occurrence was documented in a preliminary report by Narbonne and Dixon (1978); the present paper describes the paleoecology and sedimentology of these unique reefs in greater detail.

METHODS AND TERMINOLOGY

Approximately 50 sponge reefs were examined qualitatively in this study. Four, in which reef cross-section was well exposed in vertical gorge walls, were selected for detailed quantitive analysis. A vertical or horizontal band of one metre square areas was drawn across the most accessible portion of the reef section. All visible fossils greater than 1 cm^2 within each square were identified, measured and their exposed cross-sectional areas calculated. The percentage of a square represented by large visible specimens of each of the fossil groups was then calculated. Two or three samples of matrix were also collected; these were subsequently analysed in the laboratory by point counts of large (40-100 cm^2) acetate peels. The percentage of a peel represented by an individual component was multiplied by the percentage of the square occupied by matrix. This value was added to the percentage of the component visible on the surface to calculate the total percentage of the square occupied by the component. Results from several squares in the same facies of one reef were averaged to calculate the overall composition of one facies of reefal development.

Fossil composition of inter-reefal strata was quantified by a method similar to that used for the reefs, the major difference being that only macroscopic fossils were analysed.

As in the analysis of the reefs, only complete fossils were considered as paleontologic units; disarticulated brachiopod valves and crinoid pleuricolumnals were treated as sediment particles. Diagenetic fabrics on the reefs and flanking beds were studied in thin section using standard staining techniques (cf. Friedman 1959).

The extreme heterogeneity of reefs can make accurate quantification of their composition exceedingly difficult (Scoffin 1971, pp. 176-177). Several methods were applied to minimize this problem, including the use of large acetate peels rather than standard thin sections, the selection of relatively large study squares and the combination of data from several study squares within a single reef facies. Approximately 10% of the exposed area of each reef was analysed in the field, and 2-3% of the matrix in each square was analysed under the microscope. Nevertheless, some caution is needed in interpreting the results. Only major fossil groups such as classes or growth forms can be compared between facies, as variation in individual genera and species was frequently greater between study squares in the same facies than it was between squares in different facies. Variation in any major component between samples in the same facies was 10-20% for the main mass of the reef and nearly 50% for the exceedingly heterogeneous basal facies; similar values were obtained in comparisons of the same

facies in stratigraphically-equivalent reefs. Most importantly, in providing a measure of the "average" composition of a reefal facies, quantification obscures the different lithologic and faunal associations that comprise the facies. These associations are discussed in detail in the text.

Rock types were classified according to Embry and Klovan's (1971) modification of Dunham's (1962) system. In this paper, the term "reef" refers to a mound-shaped mass of fossiliferous carbonate which shows evidence of original topographic relief. Reefs can be subdivided into ecologic reefs, which exhibit features indicative of wave resistance, and stratigraphic reefs, which do not (Dunham 1970).

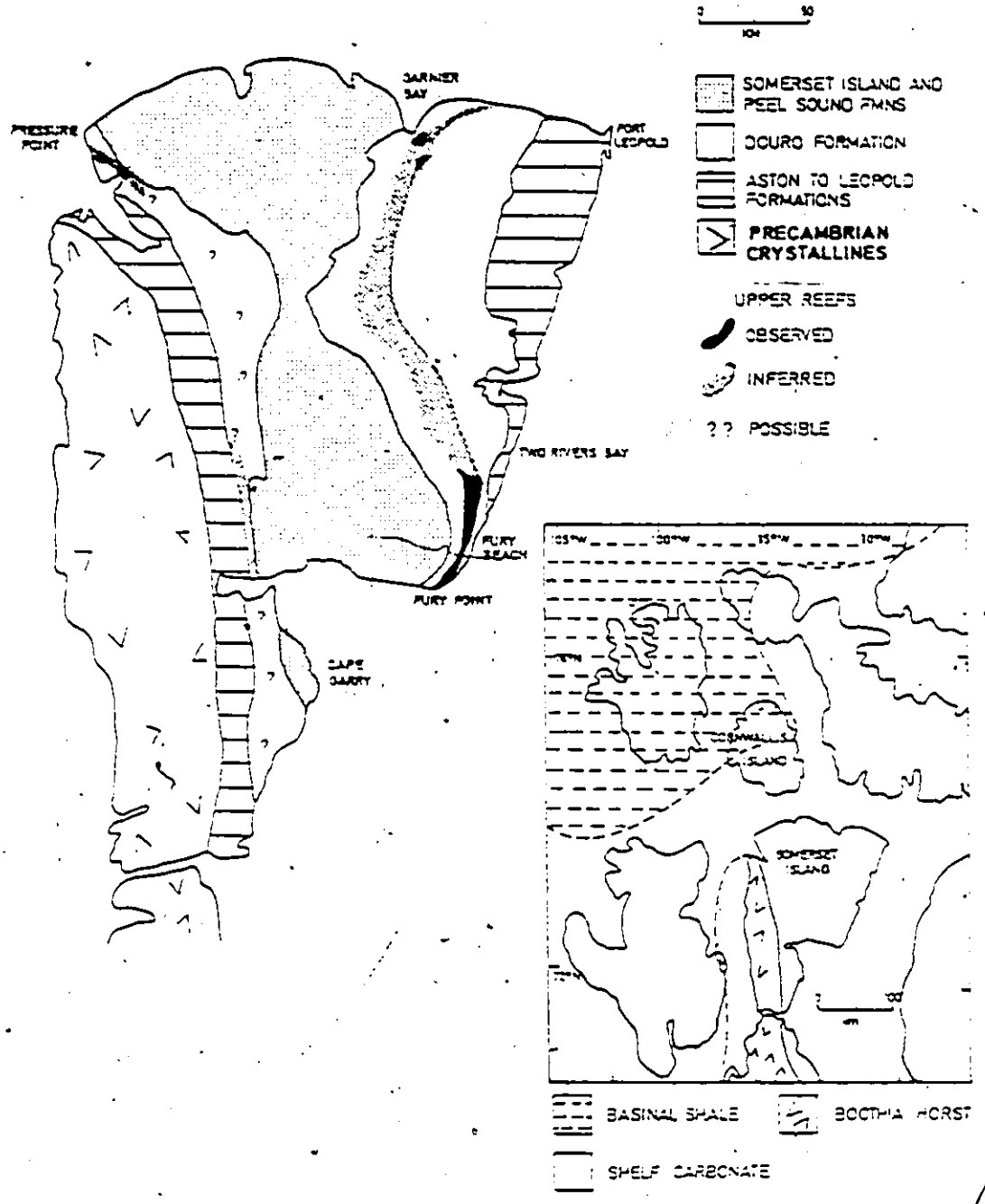
The recognition of Recent coralline sponges, the sclerosponges (Hartman and Goreau 1970), has resulted in uncertainties regarding the taxonomic position of several groups of extinct organisms formerly regarded as hydrozoans. Features typical of sponges have been observed in stromatoporoids (Hartman and Goreau 1970; Stearn 1972) and even in some tabulate corals (Flügel 1976). However, the classification of these groups with the sponges is not universally accepted (cf. Oliver 1979). Furthermore, the reef-building capacities of Silurian tabulates and stromatoporoids is not seriously in doubt; what remains to be determined is the extent to which the organisms traditionally regarded as

sponges participated in the construction of reefs. For these reasons, this paper restricts the term "sponge" to the traditional sponge classes Calcispongia (Calcarea), Hyalaspongia (Hexactinellida) and Demospongia. Stromatoporoids are not referred to any higher taxonomic division, and tabulates are regarded as corals.

GEOLOGIC SETTING

Stratigraphy and Age

The sponge reefs of this study occur on Somerset Island in the Canadian Arctic Archipelago (Text-fig. 12). Paleozoic strata on Somerset Island are more than 2 km thick, and range in age from Late Cambrian to Early Devonian (Miall and Kerr 1980). All the Upper Silurian strata were formerly referred to the Read Bay Formation of Thorsteinsson and Fortier (1954), but recent studies have indicated that it can be subdivided into four mappable formations (Part I; and references therein). The lower two, the Leopold Formation (Jones and Dixon 1975) and the Cape Storm Formation (Kerr 1975) occur at roughly equivalent levels on different parts of Somerset Island. Both units are largely composed of planar-bedded dolostone and limestone, but can be distinguished by the greater percentage of detrital units in the Leopold Formation (Dixon and



Text-fig. 12. Geographic location of the Douro Sponge Reefs.

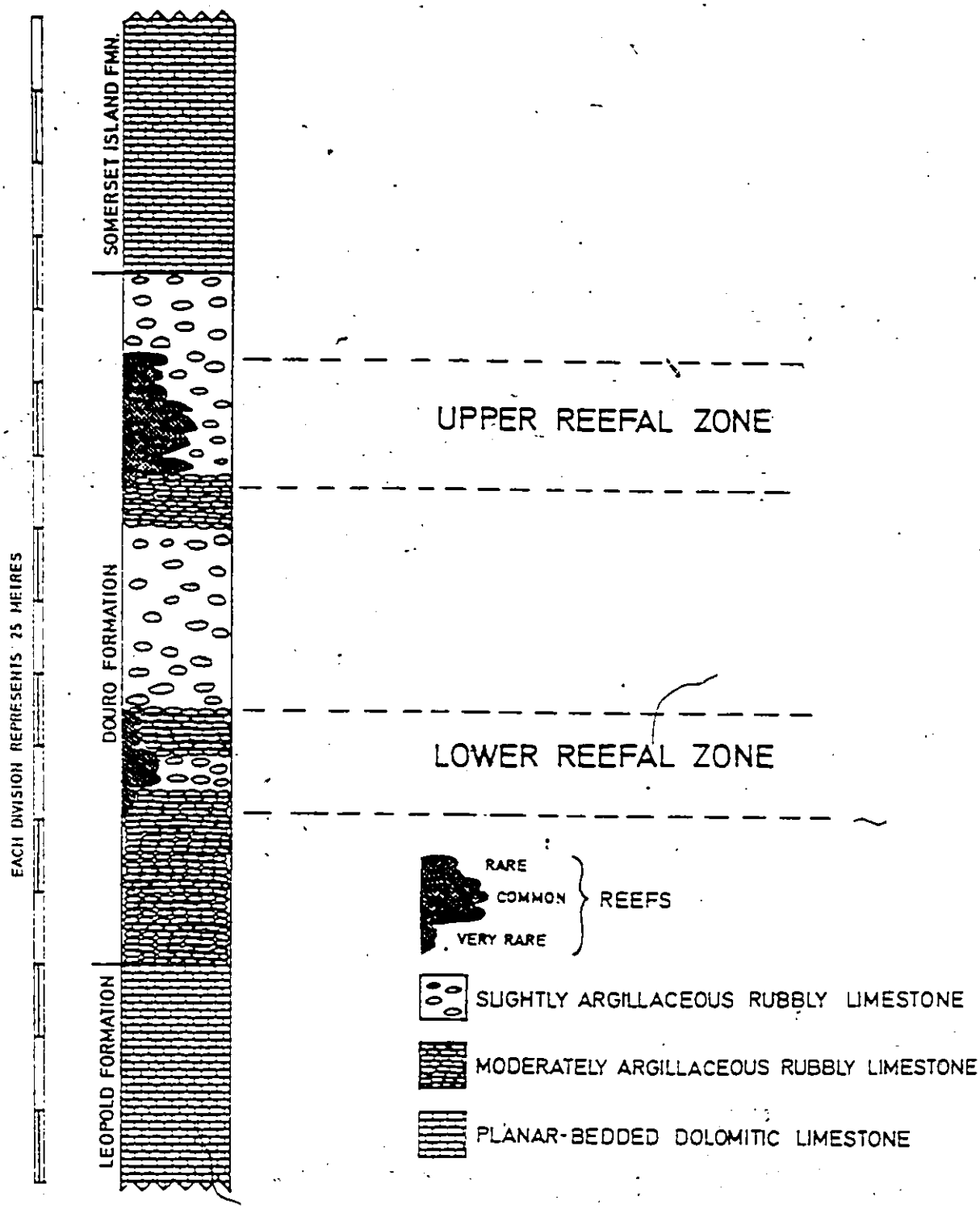
Jones 1978). Faunas and sedimentary structures suggest that both units were deposited under predominantly intertidal/supratidal conditions (Jones and Dixon 1975, 1977; Gibling and Narbonne 1977). They are overlain by the reef-bearing unit, the Douro Formation (Thorsteinsson 1963), which consists predominantly of rubbly limestone deposited under shallow subtidal conditions (Jones et al. 1979; Part I). The overlying Somerset Island Formation (Miall et al. 1978) consists of a regressive sequence of planar-bedded dolostone and limestone deposited under predominantly intertidal/supratidal conditions. The entire Upper Silurian succession is believed to be conformable (Gibling and Narbonne 1977).

On Somerset Island, the Douro Formation ranges in thickness from 180-275 m. Bryozoans above and below the reefs at Fury Point are Ludlow in age (Bolton in Narbonne 1977), and conodonts suggest a Ludlow age for reef-bearing strata at Pressure Point (Uyeno in Jones and Dixon 1977). Precise ages of other reef-bearing sections are unknown, but Thorsteinsson (in press) considered that stratigraphic relationships and available conodont dates indicate a Late Ludlow age for the Douro Formation throughout the Canadian Arctic Islands.

Distribution of Sponge Reefs

Sponge reefs occur in two distinct zones in the Douro Formation on Somerset Island (Text-fig. 13). On southeastern Somerset Island, the Lower Reefal Zone ranges approximately from 70 to 100 m above the base of the Douro Formation. Reefs are rare in the lower 10 m of this zone, and exceedingly rare in the upper 20 m. Reefs of the Lower Reefal Zone have only been observed on southeastern Somerset Island, but coral and sponge faunas typical of this interval occur at a corresponding stratigraphic level near Pressure Point to the northwest, thereby suggesting the presence of undiscovered reefs in this area as well.

On southeastern Somerset Island, the Upper Reefal Zone ranges approximately from 30 to 80 m below the top of the Douro Formation. Reefs tend to be common in the lower part of this zone and rare in the upper part. They have been observed from Fury Point in the south to Pressure Point and Garnier Bay in the north, a distance of more than 150 km. In addition, coral and sponge faunas typical of this interval occur at a corresponding stratigraphic level near Cape Garry to the southwest.



Text-fig. 13. Stratigraphic positions of the Douro Sponge Reefs.

REEFS AND ASSOCIATED DEPOSITS.

Inter-reef Deposits

More than 90% of inter-reefal deposits are rubbly limestone (Pl. 3, figs. 4,6), a rock type in which lumps or irregular lenses of dense mudstone or wackestone are surrounded by a softer matrix of shale or finely-crystalline dolomite. Sedimentologic and paleontologic evidence suggests that the lumps formed as incipient hardgrounds due to penecontemporaneous lithification; the composition of the matrix reflects both the initial composition of the sediment and the degree of diagenetic modification through selective dolomitization, calcification and pressure solution (Jones et al. 1979). Rubbly limestone in the Lower Reefal Zone contains 15-50% shale as matrix, whereas rubbly limestone in the Upper Reefal Zone contains only 10-20% shale. Rubbly limestone of both reefal intervals contains a sparse but diverse assemblage of in situ benthic fossils, chiefly the brachiopod Atrypoidea.

Thin units of planar-bedded packstone, grainstone, floatstone and mudstone occur sporadically throughout the inter-reef deposits (Pl. 3, figs. 4,6). Units exhibit erosional bases and graded bedding; they are composed predominantly of transported and broken fossil debris, chiefly

brachiopod and gastropod shells and crinoid pleuricolumnals. These units of shelly limestone closely resemble storm deposits described by Jones and Dixon (1976) from the Douro Formation of northern Somerset Island.

The basal reefal facies can directly overlie either rubbly limestone or storm-deposited clastic limestone.

Reefs

Field appearance

Reefs are composed of massive, light grey weathering mudstone and wackestone. Although sponges are the most common fossils observed in polished slabs, thin sections and acetate peels of the reefs, they are rarely evident in outcrop. In contrast, the few large corals and stromatoporoids present are readily visible in the field. For this reason, the reefs resemble coral-stromatoporoid mud mounds in their field appearance.

Reefs tend to weather resistantly due to their unbedded nature and relative scarcity of shale (Pl. 3, figs. 1,2,5). Most are subspherical; oblate and pillar-shaped structures are less common. Reefs are predominantly sub-circular in plan view, suggesting that there was no preferred directional influence on growth by currents or waves. Reefs of the Lower Zone are 5-10 m in all dimensions, whereas those of

Plate 3

Field appearance of reefs and related deposits.

Fig. 1. Three weathered-out reefs approximately 20 m high. Upper Reefal Zone at Fury Point.

Fig. 2. Large weathered-out reef. O.A. Dixon for scale. Upper Reefal Zone at Fury Point. Photo by W.G. Parkins.

Fig. 3. Basal 10 m of a reef. Note the sharp contacts between the massive mudstone (M), laterally equivalent rubbly wackestone (W) and underlying bedded crinoidal packstone(P). Upper Reefal Zone near Fury Beach.

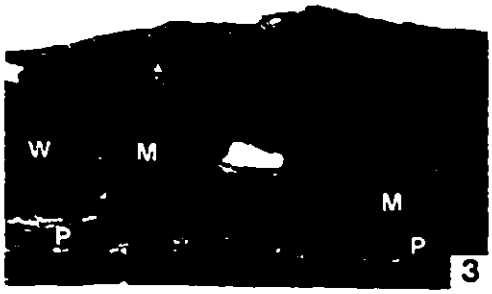
Fig. 4. Channel-fills of crinoidal packstone in inter-reefal rubbly mudstone. One medium bed of crinoidal grainstone in the lower part of the section. The hammer handle is 0.3 m long. Lower Reefal Zone near Two Rivers Bay. Photo by O.A. Dixon.

Fig. 5. Two pillar-shaped reefs fused at their tops. Note sharp contacts between massive mudstone and surrounding rubbly wackestone. M.I. Rupners for scale. Upper Reefal Zone at Fury Point.

Fig. 6. Wedge of crinoidal packstone with a transported block of reef-rock (arrowed) in inter-reefal rubbly mudstone-wackestone. One medium bed of crinoidal grainstone near top of photograph. The hammer handle is 0.3 m long. Lower Reefal Zone near Fury Beach.


1


2



3


4


5


6

Pl. 3

the Upper Zone have dimensions of 10-35 m. In general, the size and abundance of reefs is inversely proportional to the amount of argillaceous material in equivalent inter-reefal deposits.

Reefs commonly occur in small groups, with only sporadic reefal development between the clusters. Most reefs are discrete structures; only locally are adjacent reefs coalesced (Pl. 3, fig. 5). Some large, irregularly shaped structures may represent several coalesced reefs (Pl. 3, fig. 2).

Boundaries of the reefs are sharp (Pl. 3, figs. 3,5), with only minor mixing of the mudstone and surround wackestone in the outer 0.3 m of the reef. Extensive intercalation of reefal and surrounding bioclastic limestones is not evident. Minor indentations in the margins of the reefs are commonly symmetrical, and appear to be related to increases in the amount of argillaceous material in equivalent inter-reefal deposits. Most inter-reefal argillaceous seams terminate at the margins of the reef; few pass into or through the reef itself. Argillaceous seams in the reef are parallel to the bases of <u>in situ</u> corals and stromatoporoids, and thus probably represent sudden influxes of mechanically deposited mud over the reef surfaces.

Cavities and cements

Matrix constitutes approximately 50% of the reefs. Most of the matrix is lime mudstone, with less finely crystalline dolomite, fine to coarse skeletal debris and clay- to silt-sized terrigenous detritus. Much of the mudstone is micrite, but locally it has been aggraded to microspar.

Cavities ranging from 1 mm to 150 mm in length are common throughout the reefs. They are infilled geopetally with floor deposits of lime mudstone overlain by void-filling spar. Cavities rarely contain concentrations of micromorphic ostracods or gastropods, but complex cavity-dwelling faunas and floras were not observed.

Most cavities occur within corals or sponges, or between brachiopod valves (Pl. 4, figs. 1-3). Shapes of others suggest the dissolution or collapse of sponges. These relatively small cavities have floor deposits of calcilutite, much of it pelleted. Somewhat larger cavities (Pl. 4, figs. 4-6), are more irregularly shaped and exhibit floor deposits of angular calcisiltite. Scalloped walls and ceilings smoothly truncate skeletal fragments.

Three generations of sparry calcite cement occur in grainstones and in both reefal and non-reefal cavities throughout the Douro Formation (Pl. 4, figs. 3-5). The first generation comprises iron-poor, inclusion-rich, prismatic crystals 15-30 µm wide. These crystals occur on skeletal material and

Plate 4

Diagenetic features in the Douro Sponge Reefs. Symbols: C = calcilutite (predominantly pelleted); A = angular calcisiltite; S = undifferentiated spar; 1,2,3 = generations of spar cement; V = present day void; T = skeletal truncation. Scale bar represents 5 mm.

Fig. 1. Cavity in spongocoel. Positive print of an acetate peel.

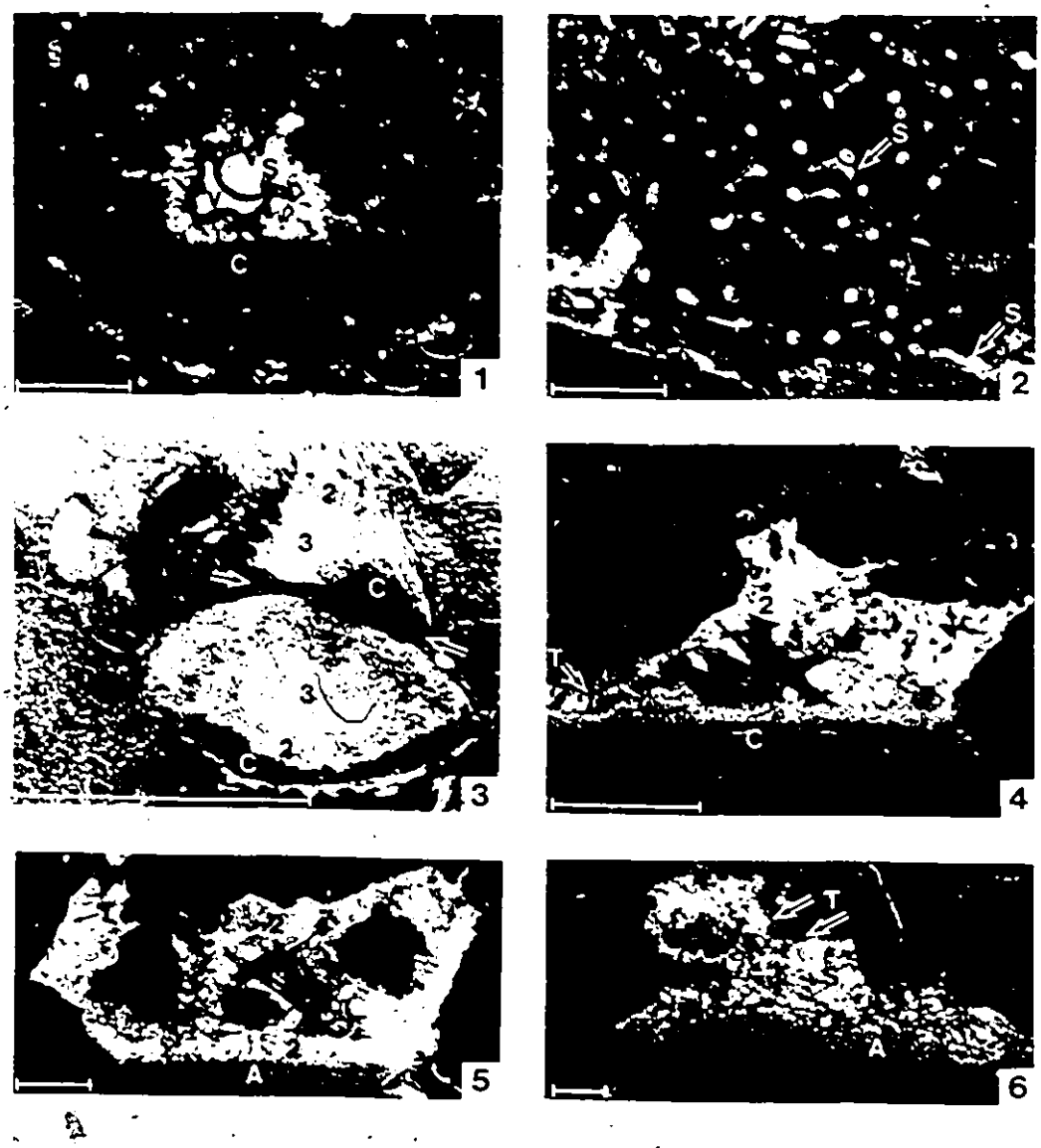
Fig. 2. Cavities within and locally (arrowed) between Syringopora tubes. Positive print of an acetate peel.

Fig. 3. Cavities between valves of the brachiopod Stegerhynchus. Note truncation of shell, sediment and spar along stylolitic seam (arrowed). Thin section in plane polarized light.

Fig. 4. Irregular cavity in stromatolitic wackestone. Note truncation of bryozoans (arrowed) across cavity ceiling. Thin section with crossed nicols.

Fig. 5. Irregular cavity with scalloped ceiling. Note truncation of crinoid (arrowed) across cavity ceiling. Thin section in plane polarized light.

Fig. 6. Irregular cavity with scalloped ceiling. Note truncation of crinoid fragment (arrowed) but not of lithistid sponge. Cavity lined by pyrite. Positive print of an acetate peel.



Pl. 4

on the roofs of cavities, most commonly in crystallographic continuity with their substrates. Generation 1 cements are locally geostrophic. The second generation is represented by inclusion-free prismatic crystals which coarsen towards the centres of cavities. This generation occurs on all substrates; it succeeds generation 1 crystals, commonly as inclusion-free extensions of the same crystal, and occurs directly on floor deposits in cavities. Variable reaction to potassium ferricyanide indicates that most generation 2 crystals are iron-free, but those nearest the centres of cavities contain small amounts of iron towards their terminations. Generation 3 comprises inclusion-free, iron-rich, prismatic to blocky crystals which coarsen towards the centres of cavities. They represent the final stage of cementation in cavities, and are the sole filling of most fractures. All three generations are cut by stylolites (Pl. 4, fig. 3).

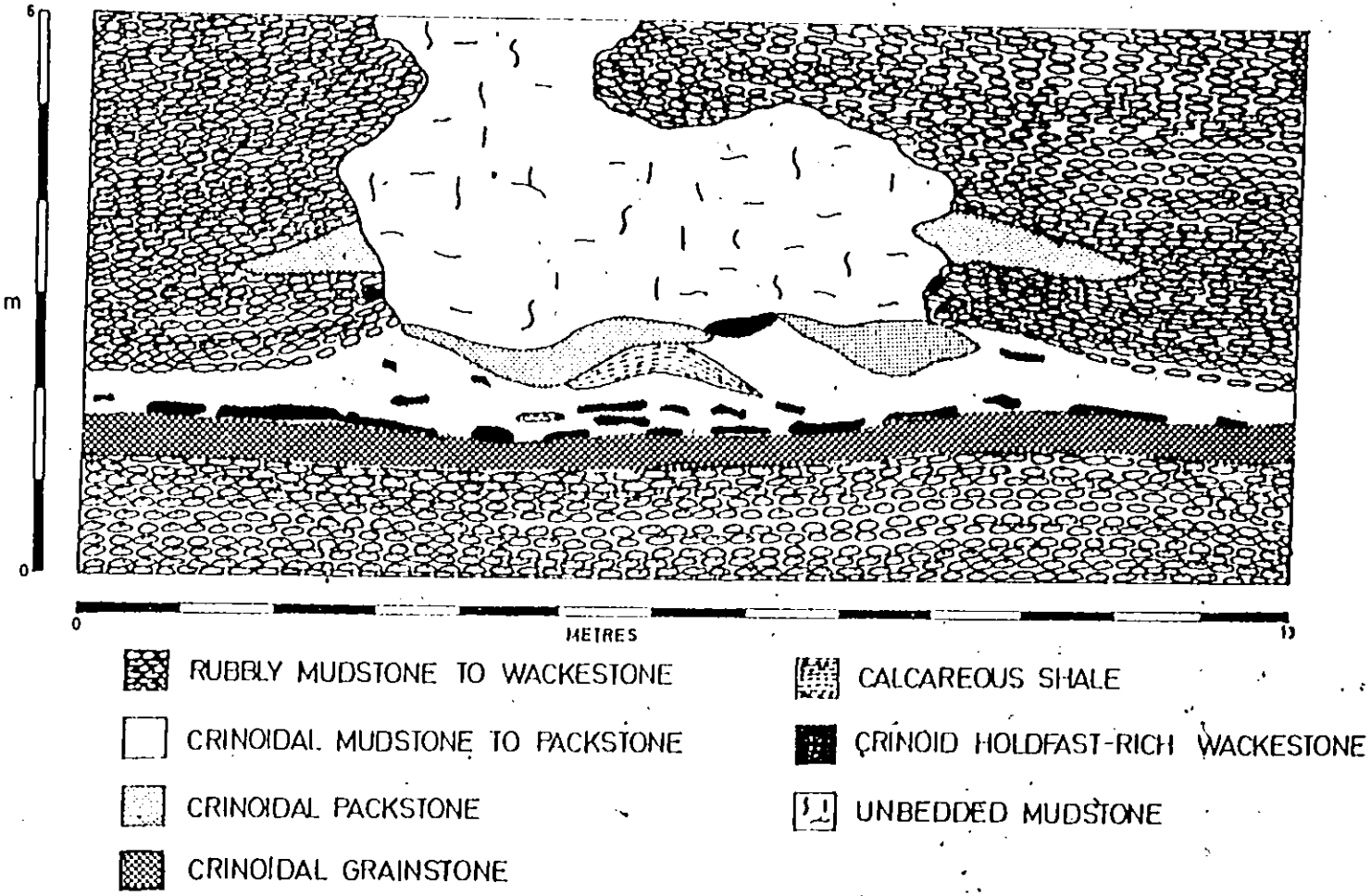
Bioclastic Limestones

Three types of bioclastic limestone are associated with the sponge reefs: a lensoid to tabular body of wackestone to grainstone underlies each reef, irregular haloes of wackestone surround most reefs, and channel-fills and wedges of packstone extend off each reef into inter-reef deposits.

Reefs are underlain by rubbly and irregularly bedded crinoidal calcarenite, predominantly packstone. Where reefs are isolated, this deposit is a lens 20-50 m long and 0.5-2.0 m thick. Where reefs are clustered, lenses commonly coalesce to form a tabular body 1-3 m thick, in which several reefs are rooted. Wackestone with abundant in situ crinoid holdfasts constitutes 5-15% of the facies. Bioclastic deposits are predominantly packstone with less wackestone, grainstone, floatstone and rudstone.

Reefs are commonly surrounded by irregularly-shaped haloes of crinoidal debris, predominantly rubbly wackestone. Crinoidal haloes are relatively narrow, passing into inter-reefal rubbly mudstone within 10-15 m of the reefs. This is accompanied by a decrease in the dips of the strata from 4-6° at the margins of the reefs to essentially horizontal at the outer limits of the haloes. Steeply dipping flank beds are not present around any of the reefs studied. Crinoidal debris was derived both in situ and from the margins of the reefs. Fossils are abundant, and include both reef-derived and autochthonous specimens.

Wedges and channel-fills of crinoidal packstone extend from the reefs into inter-reefal rubbly mudstone (Pl. 3, figs. 4,6). Crinoidal packstone exhibits planar cross-stratification, and contains numerous transported, reef-derived fossils; angular blocks of reefal boundstone 0.1 to 0.4 m in diameter occur sporadically.



Text-fig. 14. Facies relationships in the lower part of a reef. The vertical section cuts tangentially through the outer part of a reef located behind the gorge wall. Lower Reefal Zone near Two Rivers Bay.

The complex interfingering of facies associated with the lower portion of a reef is shown diagrammatically in text-figure 14.

REEF ORGANISMS

Whole fossils constitute 45-50% of the reefs. Organisms were classified according to their dominant constructive role as frame builders, binders, bafflers or dwellers (Table 2). The boundaries between these categories are not sharp: initial stages of frame builders are commonly encrusting, and the size limits of dweller and framebuilder categories are largely a function of water turbulence and thus vary from reef to reef. Furthermore, it is unlikely that all specimens of one species had exactly the same function regardless of size or abundance. Nevertheless, classification according to the dominant role of organisms provides a method of comparing organisms, both within the same reef and between reefs of different ages.

Diversity of the major fossil groups in the reefs, bioclastic haloes and inter-reef deposits of the Upper Reefal Zone is shown in Table 3. Similar trends characterize the Lower Reefal Zone. With the exception of the brachiopods and sponges, none of the fossil groups have been studied in detail taxonomically; hence all values represent the minimum number of species present.

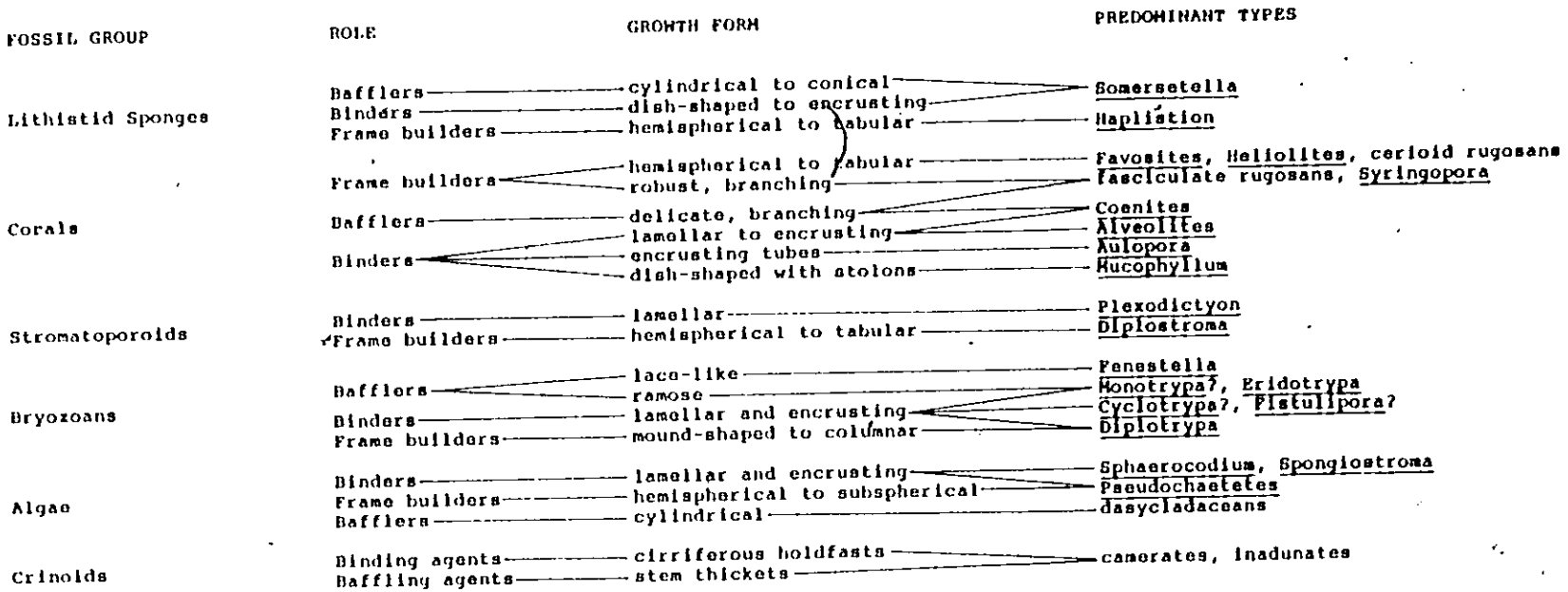


Table 2. Roles of the major fossil groups in the construction of the Douro Reefs. Roles are listed in order of decreasing importance; reef dwellers are not included.

	REEF	BIOCLASTIC HALO	INTER-REEF
Solitary Rugose Corals	2	9	2
Compound Rugose Corals	5	7	1
Tabulate Corals	15	16	4
Stromatoporoids	2	1	0
Sponges	6	3	2
Algae	6	2	1
Crinoids	2	3	1
Bryozoans	4	2	1
Brachiopods	5	5	5
Trilobites	1	2	1
Ostracods	2	2	2
Molluscs	6	6	4
Others	2	2	2
TOTAL	58	60	26

Table 3. Minimum species diversity of the major fossil groups in the Upper Reefal Zone.

Sponges

Reefal intervals in the Douro Formation contain abundant lithistid demosponges along with fewer hyalosponges and rare calcisponge spicules. Rigby and Dixon (1979) described nine species of lithistids and one hyalosponge species, all of them previously undescribed.

Specimens and isolated spicules of hyalosponges are most common in reefal zones, but were only rarely observed in the reefs *per se*. In contrast, lithistid sponges are the most common fossils in the reefs, constituting an average of 35% of the rock. Some slabs contain up to 70% *in situ* lithistids.

A variety of lithistid growth forms are present (Pl. 5). The vast majority are thin-walled, conical to cylindrical anthaspidellids 2-12 cm high. These were too small and fragile to have functioned as frame builders, but were probably effective sediment bafflers. Massive, hemispherical to tabular forms up to 12 cm in diameter were probably small frame builders. Lamellar, encrusting and bowl-shaped forms up to 10 cm in diameter may have been binders. Cylindrical and conical forms occur rarely in bioclastic haloes and even in inter-reefal and non-reefal deposits; massive and bowl-shaped specimens were only observed *in situ* in reef-rock. Lithistids are very rare in non-reefal strata.

Plate 5

Growth forms of lithistid sponges in the Douro Sponge Reefs. Figs. 1,5 Haplistion; Figs. 2,3,4,6 Somersetella.

Fig. 1. Tabular

Fig. 2. Cylindrical

Fig. 3. Lamellar to bowl-shaped

Fig. 4. Conical

Fig. 5. Hemispherical

Fig. 6. Conico-cylindrical

Pl. 5

Corals

Although specimens of Favosites, Syringopora, Aulopora and solitary rugosans occur sporadically throughout the Douro Formation, the abundance and diversity of corals is greatest in reefal intervals. Field identifications suggest that more than 80% of coral species are restricted to reefal facies. Dixon (1979) discussed the taxonomy of some heliolitid corals from Garnier Bay, and W.G. Parkins (in preparation) is studying the taxonomy and paleoecology of the solitary rugosans, but the remainder of the fauna has not yet been studied systematically.

Corals are rare in inter-reefal mudstone, but are abundant in haloes of crinoidal wackestone surrounding the reefs. Similarly, corals constitute only 2-3% of mudstone but more than 20% of wackestone facies within the reefs. This distribution may reflect preferential attachment to hard substrates by the larvae.

A variety of coral growth forms filled most major constructional roles (Table 2). As in modern coralgal reefs, the principal role was that of frame-building. A few hemispherical Favosites colonies greater than 0.5 m in diameter are present, but the majority of the hemispherical and tabular corals are only 5-10 cm in diameter. Corals are isolated, and only rarely form an interlocking framework. These forms probably functioned as frame-builders in a

relatively calm environment, but could not have formed a rigid framework capable of resisting oceanic waves. Encrusting forms are locally common (Pl. 6, fig. 1).

Halysitid corals are common in most Silurian reefs. Their apparent absence from the Douro Sponge Reefs is problematic, particularly in view of their occurrence in Upper Silurian reefs on Cornwallis Island to the north (Packard and Dixon 1979).

Stromatoporoids

Although stromatoporoid biostromes are present in formations immediately underlying and overlying the Douro Formation, stromatoporoids are rare in the rubbly limestone of the Douro Formation (Savelle 1979). Stromatoporoids in the Douro Formation are apparently restricted to reefal intervals. Their distribution is similar to that of the corals, in that they occur most commonly in crinoidal wackestone, especially at the tops of reefs. Stromatoporoids functioned as both binders and frame builders.

Bryozoans

Trepostomate, cyclostomate and cryptostomate bryozoans occur sporadically throughout the Douro Formation (Bolton 1966). A more diverse assemblage, comprising more than ten

Plate 6

Fauna from a reef of the Lower Zone north of Fury Beach. Scale bar represents 2 cm.

Fig. 1. Stromatoporoid and encrusting Coenites (tabulate coral) in wackestone matrix. Base of specimen parallel to geopetal structures.

Fig. 2. Monotrypa? (trepostomate bryozoan) exhibiting encrusting and ramose habits. Packstone and grainstone matrix.

Fig. 3. Columnar Diplotrypa (trepostomate bryozoan) and discoid crinoid holdfasts in packstone matrix.

Fig. 4. Cirriferous crinoid holdfasts in wackestone matrix.

Pl. 6

species, is found in the reefs. None of the species of reefal bryozoans has been observed in inter-reefal or non-reefal deposits (T.E.Bolton, pers.comm., 1980).

Bryozoan growth forms were relatively "plastic". One specimen of Monotrypa? (Pl. 6, fig. 2) shows a change from an encrusting to a ramose habit following the death and collapse of its initial support (a crinoid stem). The same species of Diplotrypa can occur as a small mound-shaped body, a lamellar sheet over sediment or an encrustation on skeletal material. Locally, repeated thin encrustations of Diplotrypa have resulted in spherical and columnar forms similar to algal oncolites and stromatolites (Pl. 6, fig. 3).

Although bryozoans constituted a relatively small portion of the fauna, they played a major role in reef construction. Lamellar sheets grew over the reef surface, binding in situ skeletons and the intervening sediments into a solid structure. Locally, bryozoans and auloporids are intensely intergrown to form a solid framework. Bryozoans also functioned as bafflers and small frame-builders. The participation of bryozoans in a wide variety of constructive roles is a common feature of many early Paleozoic reefs (Cuffey 1976).

Algae

Calcareous algae are common in the reefs, constituting more than 10% of some facies. Most genera are restricted to

the mounds, but the solenoporid Pseudochaetetes also occurs in inter-reefal and non-reefal deposits.

Blue-green, green and red algae functioned as binders, encrusting skeletal material and growing as lamellar sheets over the sediment. Algae commonly encrusted other algae to form complicated successions (Pl. 7A); the sequence of encrustation by the different genera was apparently random. Hemispherical to subspherical masses of Pseudochaetetes up to 7 cm in diameter may have been small frame builders. Thin-walled dasycladaceans, 2-4 mm in diameter and approximately 1 cm long, occur in local concentrations which probably represent thickets of baffling organisms (Pl. 9, figs. 1,2).

Crinoids

Unlike other reef builders, crinoids had highly differentiated skeletons, with each part fulfilling a different constructional role. Holdfasts ('root systems') and stems were the most important crinoid elements in reefal construction.

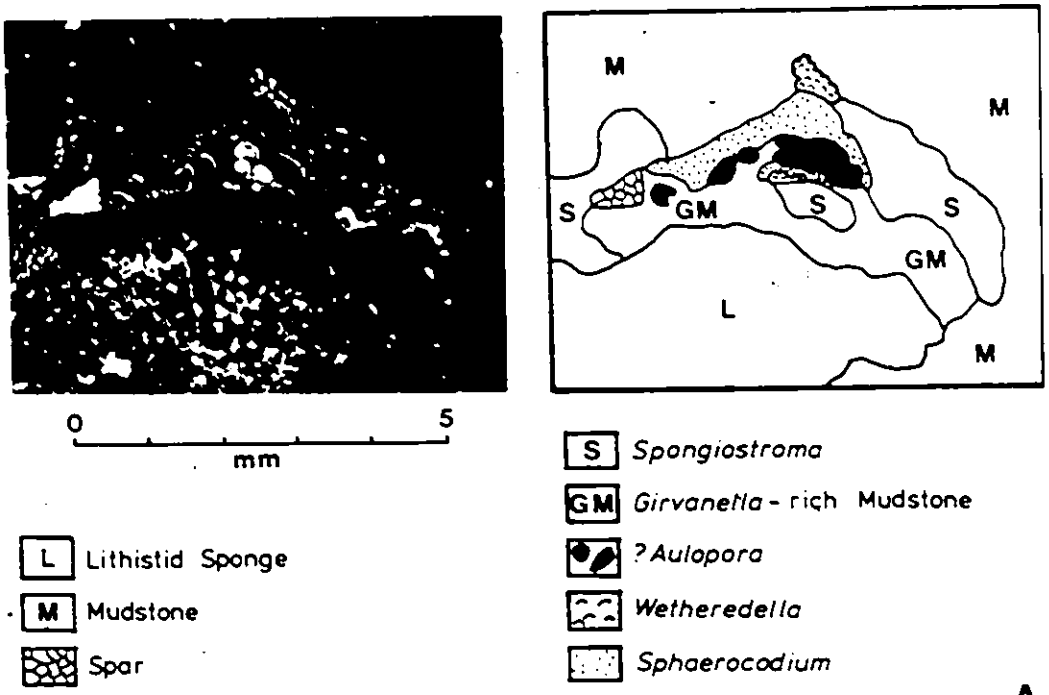
Franzén (1977) recognized four major morphologic groups of Silurian crinoid holdfasts, two of which are present in the Douro Sponge Reefs. Small circular to digitate discoid holdfasts are cemented on large bryozoan, coral and stromatoporoid skeletons. Cirriferous holdfasts consist of root-like networks of repeatedly branching radicular cirri or pseudocirri. Most

Plate 7A

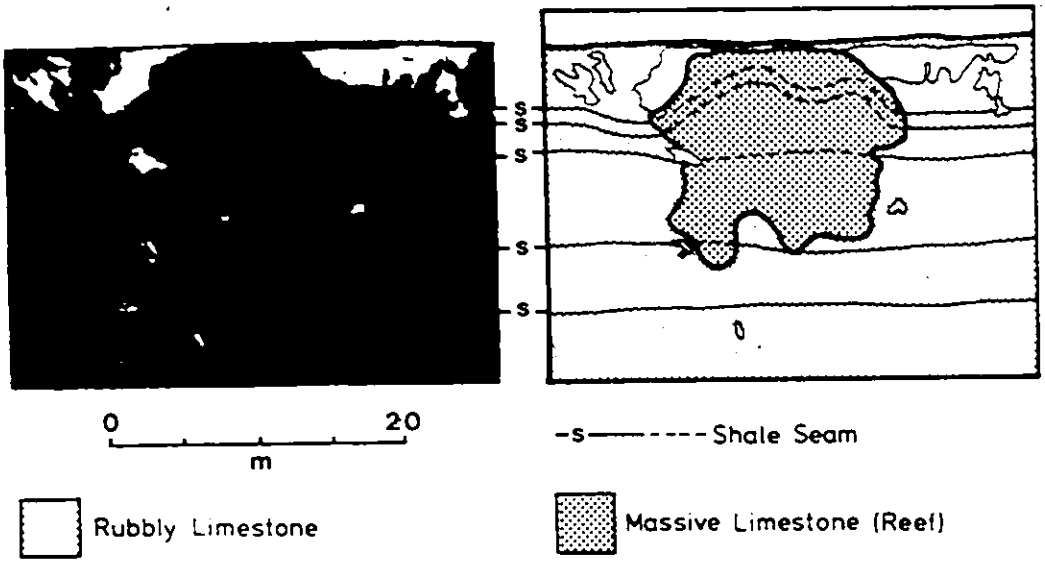
Photograph and line drawing of algal and ?coral encrustations on a sponge.

Plate 7B

Photograph and line drawing of a reef of the Upper Zone near Fury Beach. Note the increasing relief of the shale seams upward through the reef.


M
M
S
GM
S
S
GM
L
M
0
5
mm
L Lithistid Sponge
M Mudstone
Spar
S Spongiostroma
GM Girvanella - rich Mudstone
? Aulopora
Wetheredella
Sphaerocodium

A


s
s
s
s
s
0
20
m
-s---- Shale Seam
Rubbly Limestone
Massive Limestone (Reef)

B

Pl. 7

of the cirriferous holdfasts in these reefs are complexly intergrown networks of pseudocirri which branch radially off a main stem (Pl. 6, fig. 4). The radial pattern of branching and the occurrence of bryozoan encrustations almost exclusively on the uppermost pseudocirri suggest that the root system formed within the sediment with only its uppermost parts exposed on the sea floor. The dense intergrown pattern of cirriferous holdfasts suggests that they were effective sediment binders, much like the rhizoid systems of most Cenozoic seagrasses.

Crinoid stems assisted in reefal construction in several ways. Dense thickets of stems were sediment bafflers, and disarticulation of the pleuricolumnals following the death of the crinoid released large volumes of sand-sized sediment. In addition, stems of living crinoids formed attachment sites for brachiopods and encrusting bryozoans, further increasing the reef mass. Crinoids combined baffling, binding and sediment-producing roles, and were undoubtedly important reef builders.

As in most other Silurian sequences, crinoids are closely associated with the reefs. Discoid holdfasts and small accumulations of pleuricolumnals occur sporadically throughout the Douro Formation, but cirriferous holdfasts and pleuricolumnals greater than 5 mm in diameter were observed only in reefal intervals. Although large deposits of crinoidal debris

surround the reefs, calices are rare. To date, the camerate Carpocrinus is the only crinoid calyx identified from these reefs (Frest and Strimple 1977; Narbonne 1977).

Others

Brachiopods, gastropods, ostracods, trilobites, nautiloids, bivalves, cornulitids and probable echinoids were dwellers on the reefs. Representatives of all these groups occur throughout the Douro Formation, but there is considerable difference at the generic level between reefal and inter-reefal assemblages. Several species of brachiopods, gastropods and trilobites were apparently endemic to the reefs.

The Douro Formation contains a diverse assemblage of trace fossils (Part III). Bioturbate textures are common in the reefs, although the scarcity of lithologic interfaces or selectively dolomitized burrows makes specific identification difficult. Palaeophycus and Teichichnus were the only burrows identified.

LATERAL ZONATION

Intramound

Quantitative and qualitative analyses of lateral variation in composition revealed few consistent patterns. Crinoid

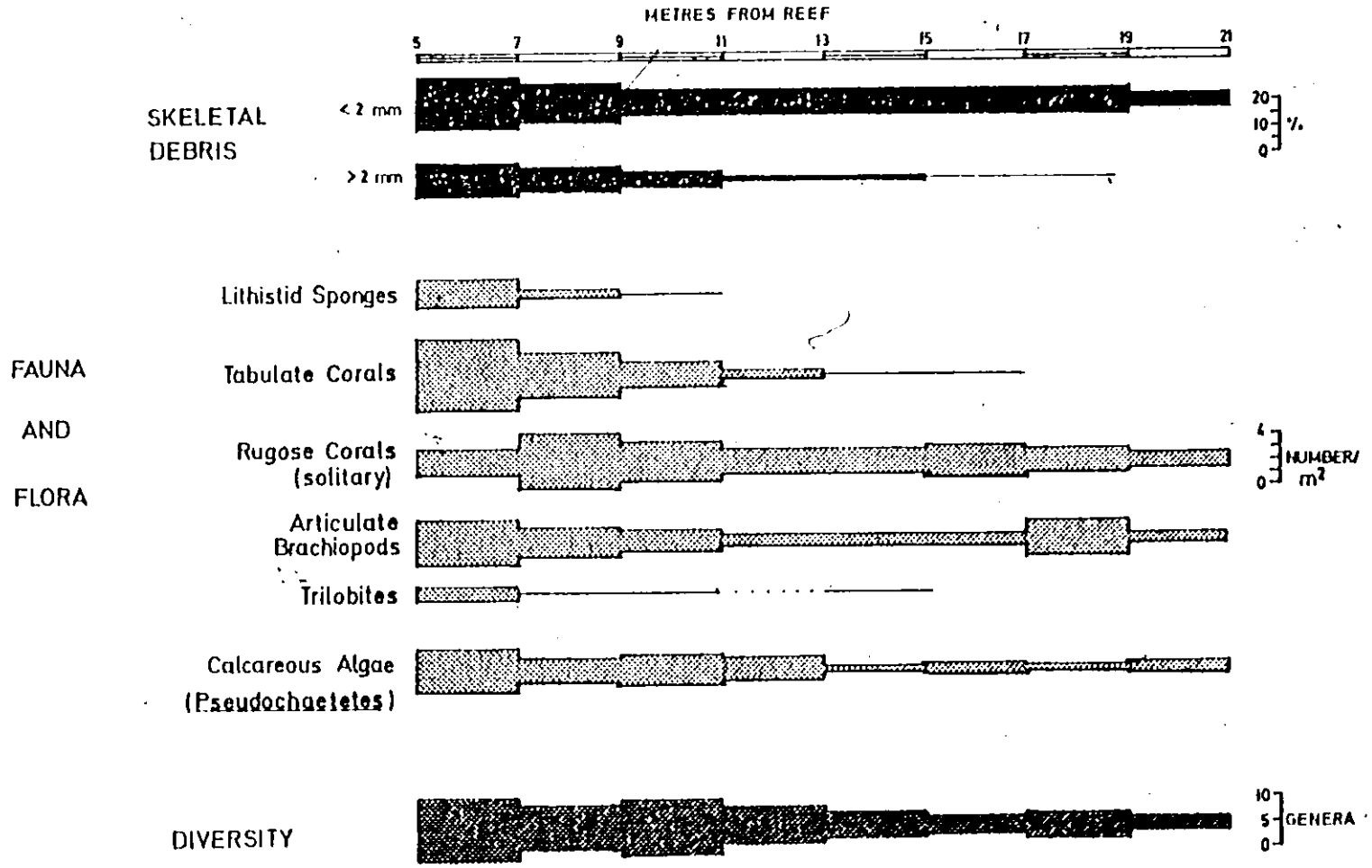
holdfasts occur most commonly along the margins of the reefs, and are locally associated with coral-rich crinoidal wackestone. Distribution of all other paleontologic and sedimentologic components, although patchy, showed no consistent lateral variation.

Bioclastic Haloes

In contrast with the poorly developed lateral zonation of the reefs, bioclastic haloes exhibit consistent lateral zonation. All paleontologic and sedimentologic components vary regularly with distance from the reef. Results of a quantitative analysis of a single bedding surface beginning 5 m from a reef (Upper Reefal Zone, Fury Point) are shown diagrammatically in text-figure 15.

Some aspects of the zonation shown in text-figure 15 warrant special comment. The percentage of skeletal material in the rock and the average bioclast size both decrease markedly away from the reef. Disarticulated crinoid pleuricolumnals constitute more than 80% of skeletal debris; the distribution of holdfasts suggests that most of the crinoidal debris was derived from within two metres of the reef.

Fossils decrease in numbers and diversity away from the reef. Reef builders (sponges, corals, algae, bryozoans and crinoids) decrease most markedly; reefal dwellers (brachiopods,



Text-fig. 15. Distribution of skeletal debris and fossils along a bedding plane flanking a reef of the Upper Zone near Fury Point.

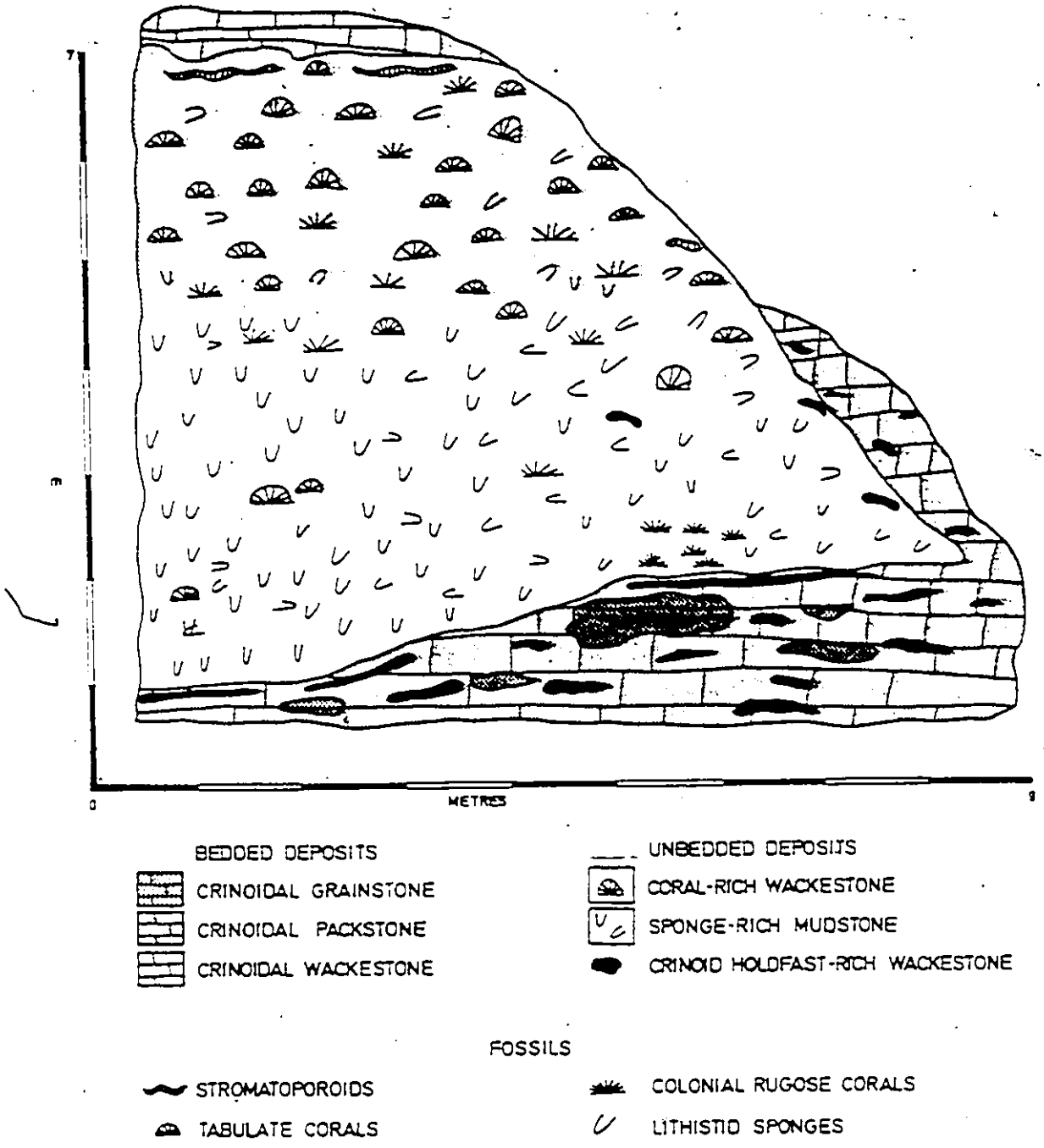
molluscs, arthropods, etc.) show lesser decreases. Mean size of some colonial organisms (e.g. Favosites, Pseudochaetetes) also tends to decrease away from the reef. With the exception of disarticulated crinoidal debris and fossils in bioclastic channel deposits and wedges, most fossils did not undergo extensive transportation. Fossils, particularly near the reef, are commonly overturned but rarely show signs of wear. Reefal blocks and reef-derived fossils in bioclastic haloes were only observed within 2 m of the reef.

This zonation can be observed around many isolated reefs. Where reefs are closely spaced, lateral zonation is less obvious due to coalescence of bioclastic haloes. In general, reefal development only affected those sediments within 15 m of the margins of a reef.

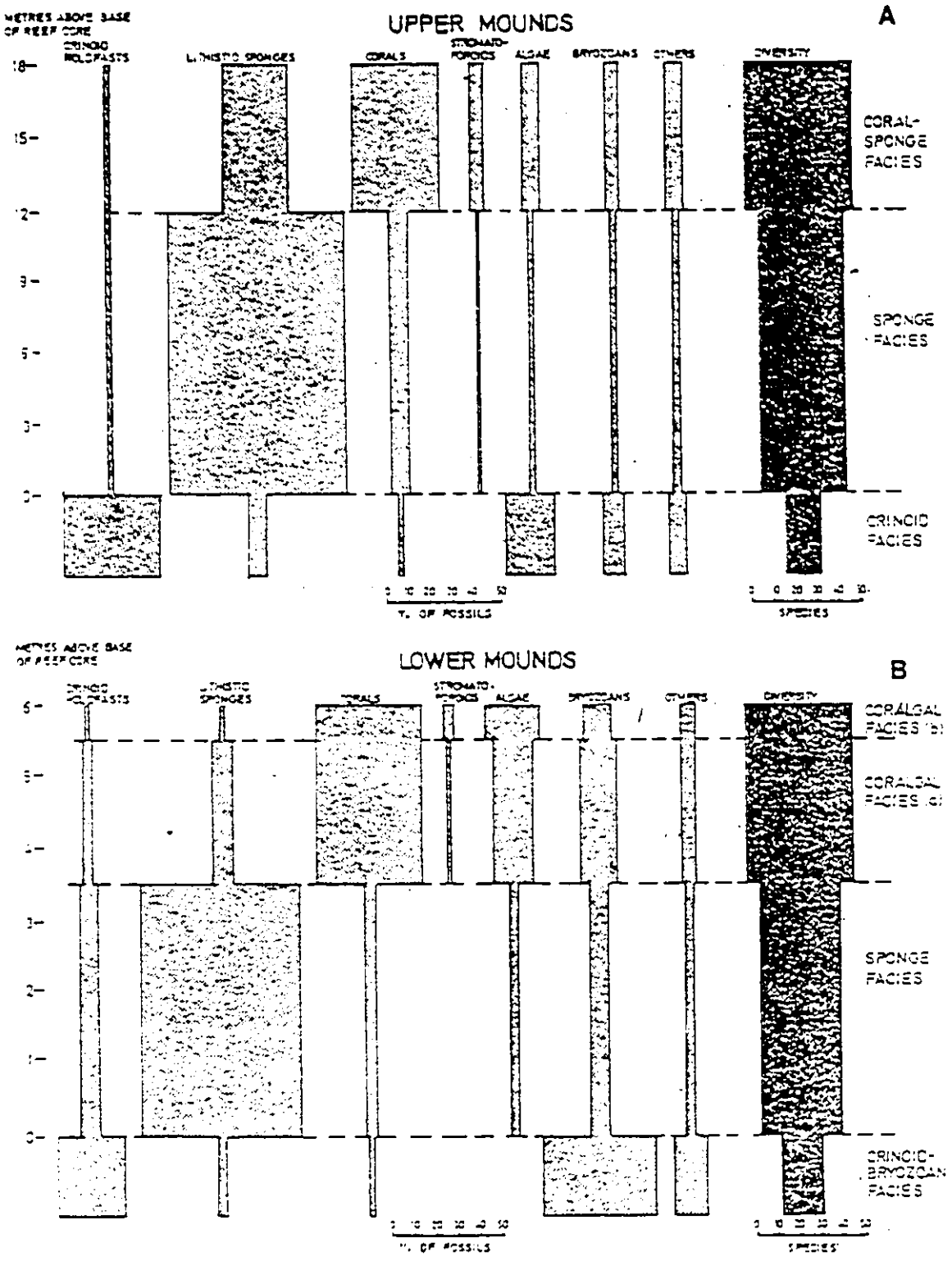
VERTICAL ZONATION

Lower Reefs

Qualitative studies of reefs from Fury Point to Two Rivers Bay (Text-fig. 12) suggested a consistent vertical zonation of lithology and fossil content. A well-exposed reef north of Fury Beach (Text-fig. 16) was selected for detailed quantitative analysis of this zonation (Text-fig. 17B).



Text-fig. 16. Vertical section of half of a reef, showing faunal and facies relationships. White areas represent areas of no exposure. Lower Zone north of Fury Beach.



Text-fig. 17. Comparison of vertical zonation of fossils in reefs of the Upper and Lower Zones.

Crinoid-Bryozoan Facies

Reefs are underlain by elongate lenses of bedded bioclastic debris. Lenses are 0.5-2 m thick, and are composed predominantly of crinoidal debris, chiefly packstone. Irregular lenses of grainstone, floatstone, rudstone, crinoid holdfast-rich mudstone to wackestone (Pl. 6, fig. 4), bryozoan-rich mudstone to packstone (Pl. 6, figs. 2,3), and brachiopod-rich wackestone to packstone (Pl. 4, fig. 3) occur sporadically throughout the packstone. Boundaries of the various lithotypes vary from gradational to erosional.

Complete fossils, chiefly crinoid holdfasts and bryozoans, constitute approximately 30% of the facies by volume. Most crinoid holdfasts are cirriferous, chiefly rhizoid holdfasts with fewer Rhizocrinus-like holdfasts; discoid holdfasts are rare. Bryozoans display a wide variety of growth forms. Mound-shaped, columnar and encrusting Diplotrypa occur in mudstone and crinoidal wackestone. Ramose Monotrypa? occurs in all lithotypes but is most common in packstone; Cyclotrypa? encrusts crinoids throughout the facies.

The articulate brachiopods Stegerhynchus, Atrypoidea, Gypidula and Tannuspirifer are common. The small rhynchonellid Stegerhynchus is particularly abundant, constituting 2-3% of the facies by volume. In contrast to the other brachiopods, which are predominantly in life position (cf. Smith 1976, pp. 16-17), specimens of Stegerhynchus show no preferred

orientation. They may have been attached to crinoids by their pedicle, falling into random positions following the death of the brachiopod or crinoid (cf. Halleck 1973).

A variety of simple and spinose gastropods are common. Leperditiid ostracods, lithistid sponges (Somersetella), and corals (Syringopora, Aulopora, fasciculate and solitary rugosans) are very rare. In total, approximately 20 species were observed.

Sponge Facies

Unbedded mudstone of the sponge facies overlies bedded packstone of the crinoid-bryozoan facies with sharp contact. The sponge facies consists of richly fossiliferous lime mudstone (Pl. 8) with less than 3% broken fossil debris. This relatively homogeneous facies constitutes the bulk of the mounds.

Lithistid sponges constitute almost 80% of the fossils by volume (Pl. 8). Sponges comprise cylindrical and conical anthaspidellids (Somersetella) with fewer dish-shaped and massive hemispherical forms. Cirriferous and discoid crinoid holdfasts are common, but are much less important than in the underlying facies. Bryozoans comprise lamellar and encrusting Diplotrypa and Cyclotrypa?, and rare ramose and fenestellid forms. Encrusting algae (Spongiostroma, Girvanella, Sphaerocodium, Pseudochaetetes and the possible

Plate 8

Sponge-rich facies from a reef of the Lower Reefal Zone north of Fury Beach. Symbols: S = spar-filled cavity; H = crinoid holdfast; L = lithistid sponge. Positive print of an acetate peel. Scale bar represents 1 cm.

Pl. 8

alga Wetheredella) are rare; ramose algae (dasycladaceans) are very rare. Corals occur rarely. Most corals are hemispherical to spherical colonies of Favosites and delicate fasciculate (chiefly dendroid) rugosans, with fewer Syringopora, Aulopora, streptelasmatids and conical mucophyllids. Brachiopods (Stegerhynchus, Atrypoidea and indeterminate small articulates), gastropods, ostracods and trilobites are rare. In total, approximately 35 species were observed.

Coralgal Facies

Richly fossiliferous, unbedded, shelly and crinoidal wackestone (Pl. 9, fig. 1) of the coralgal facies caps the reefs. The boundary between the sponge and coralgal facies is gradational over 0.3-0.5 m.

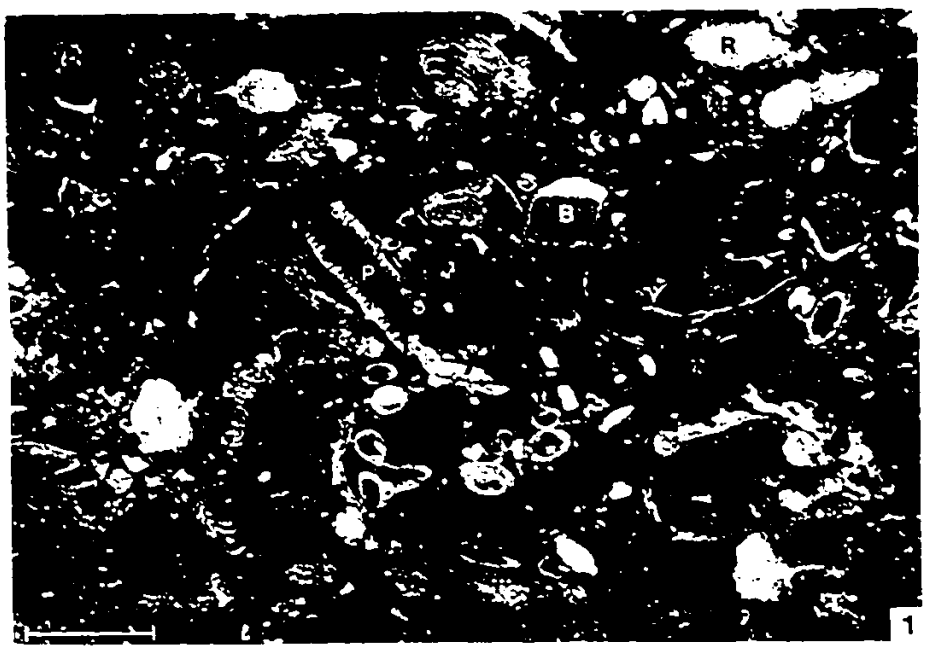
Corals are abundant, constituting almost 50% of the fossil assemblage (by volume). Most colonies are hemispherical, but the uppermost 0.5 m of the mound contains numerous tabular and lamellar forms (Pl. 6, fig. 1). The lower part of the facies contains, in approximate order of abundance, Syringopora, foliate Coenites, Favosites, cerioid rugosans, fasciculate rugosans, conical mucophyllids and streptelasmatids. The upper part of the facies contains Syringopora, lamellar Coenites, fasciculate rugosans, foliate Coenites, cerioid rugosans, Favosites, Alveolites, dish-shaped

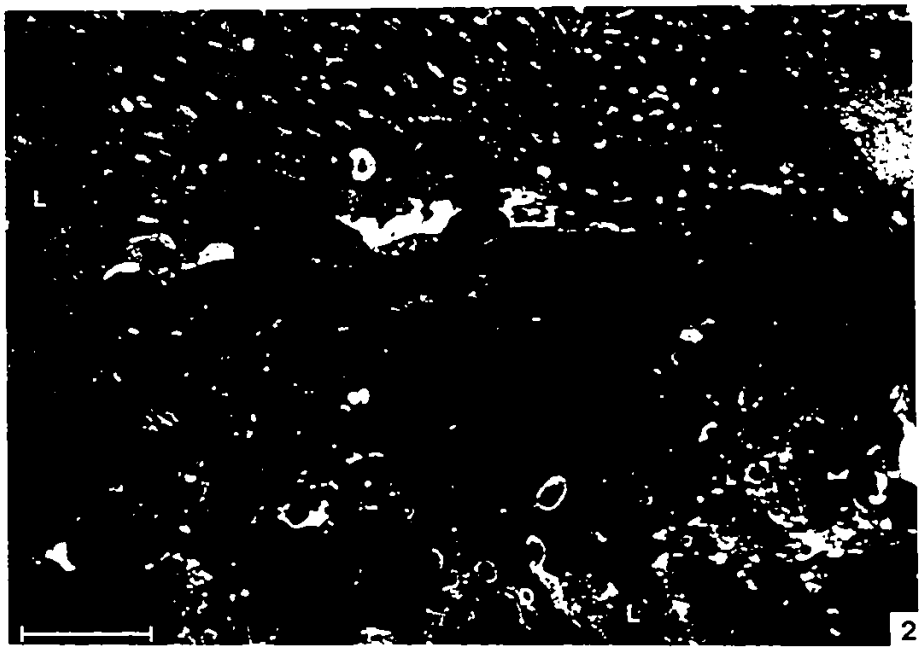
Plate 9

Coral-rich facies of the Douro Sponge Reefs. Positive prints of acetate peels. Scale bar represents 1 cm.

Fig. 1. Lower Reef north of Fury Beach. Symbols: C = foliate Coenites (tabulate coral); R = fasciculate rugose coral; A = spongiostromate algae; D = dasycladacean algae; P = crinoid pleuricolumnal; B = brachiopod; T = trepostomate bryozoan.

Fig. 2. Upper Reef at Fury Point. Symbols: S = Syringopora (tabulate coral); R = cerioid rugose coral; L = lithistid sponge; D = dasycladacean algae.





Pl. 9

mucophyllids, streptelasmatids and Heliolites. Stromatoporoids occur rarely in the lower part of the facies and commonly in the upper part. Algae (same genera as in sponge facies) are abundant throughout the facies, but dasycladaceans and Pseudochaetetes are especially common in the upper part. Bryozoans are common, and include Cyclotrypa?, Fistulipora?, Monotrypa? and indeterminate ramose trepostomates. Crinoid holdfasts (cirriferous and discoid), lithistid sponges (chiefly Somersetella), brachiopods (Atrypoidea, Atrypa, Stegerhynchus and indeterminate articulates), gastropods, ostracods, trilobites and cornulitids are rare. In total, approximately 50 species were observed.

Upper Reefs

Reefs from Fury Point to north of Fury Beach exhibit a consistent vertical zonation of lithology and fossil content. Unfortunately, no well-exposed and accessible section was found through an entire reef of the Upper Zone. As a consequence, parts of three reefs were studied in detail: the two lower facies were studied quantitatively in reefs at Fury Point and Fury Beach, and the uppermost facies was studied semiquantitatively in a reef at Fury Point. A composite of the two studies at Fury Point is shown in text-figure 17A.

Crinoid Facies

Reefs are underlain by a lensoid to tabular body of crinoidal debris, chiefly packstone, with less grainstone, floatstone, rudstone and holdfast-rich wackestone. Complete fossils constitute approximately 20% of the facies by volume. Almost half the fossils (by volume) are crinoid holdfasts. Most holdfasts are cirriferous, chiefly rhizoid holdfasts with fewer large radices with stout cirri; discoid holdfasts are very rare. Mound-shaped specimens of the sokenoporid alga Pseudochaetetes are very common. Conical anthaspidellid sponges (Somersetella) and bryozoans (ramose Monotrypa) are rare; corals (Syringopora, Aulopora, streptelasmatids and foliate Coenites), brachiopods (Atrypoidea, Stegerhynchus and Gypidula) and gastropods are very rare. In total, approximately 15 species were observed.

Sponge Facies

The crinoid facies is overlain by unbedded mudstone rich in sponges. Most of the mudstone contains less than 4% broken skeletal material, but irregular lenses of crinoidal wackestone with numerous corals occur sporadically throughout the mudstone.

Lithistid sponges constitute more than 80% of the fossil assemblage by volume. Sponges comprise mainly cylindrical, conical and encrusting forms with fewer dish-shaped and massive

hemispherical forms. Corals occur rarely, and comprise hemispherical to lamellar (predominantly tabular) specimens of Favosites, Syringopora, cerioid rugosans, Aulopora, Heliolites and lamellar Coenites along with fasciculate rugosans, foliate Coenites, dish-shaped mucophyllids and streptelasmatids. Crinoid holdfasts (mainly rhizoid holdfasts), stromatoporoids (lamellar and tabular), algae (Spongiostroma and Girvanella), bryozoans (Monotrypa, Eridotrypa, Fistulipora? and Fenestella?), brachiopods (Atrypoidea, Stegerhynchus and indeterminate articulates), gastropods, trilobites and ostracods are very rare. In total, approximately 40 species were observed.

Coral-Sponge Facies

Unbedded, crinoidal and shelly wackestone rich in corals and sponges (Pl. 9, fig. 2) caps the reefs of the Upper Interval. The contact with the underlying sponge facies was not observed.

Corals are, volumetrically, the most important fossils in this facies. Growth forms are similar to those of the Sponge Facies, and do not change markedly towards the top of the reef. Corals comprise Favosites, Syringopora, cerioid rugosans, dish-shaped mucophyllids, Heliolites, fasciculate rugosans, Aulopora, streptelasmatids and Thecia. Sponges are common, and comprise encrusting cylindrical and conical forms

with fewer dish-shaped and massive hemispherical specimens. Stromatoporoids (chiefly tabular forms), algae (Pseudochaetetes, Spongiostroma, Girvanella and ramose dasycladaceans) and bryozoans (Fenestella, ramose Eridotrypa and Monotrypa, and encrusting Fistulipora?) are rare. Brachiopods (Atrypoidea and indeterminate articulates), gastropods, ostracods, trilobites and cornulitids are very rare. In total, approximately 50 species were observed.

Bioclastic Haloes

As previously demonstrated, the fossil composition of the bioclastic haloes differs considerably from that of laterally equivalent reefal deposits. However, most trends present in the zonation of the mounds are mirrored in the bioclastic haloes. For example, whereas the percentage of corals and stromatoporoids increases upwards through the bioclastic beds, the percentage of sponges decreases..

REEF GROWTH

Environmental Setting

Based on paleomagnetic evidence (Irving 1979; Scotese et al. 1979), the Late Silurian position of Somerset Island was probably 10-20° north of the equator. This would suggest a warm climate, a view supported by the faunal and floral

composition of the reefs. Sabkha evaporites in the overlying and underlying formations (Jones and Dixon 1975; Miall et al. 1978; Reinson 1978) further suggest hot arid conditions.

Silurian strata of the southeastern Canadian Arctic Islands are divided by a major east-west facies boundary passing through Cornwallis Island (Text-fig. 12). North of this boundary, graptolitic shales accumulated in a deep-water basin, while south of this boundary shelly limestones were deposited on the shelf (Gibling and Narbonne 1977). The sponge reefs grew on a broad carbonate shelf, 100-250 km south of the shelf margin. To the west, the Boothia Horst was submerged, but may have exerted a shoaling influence (Jones and Dixon 1977).

The fossils and sedimentary structures of the Douro Formation are typical of deposits formed under subtidal conditions of normal to slightly elevated marine salinities (Veizer et al. 1978; Jones et al. 1979). The occurrence of large numbers of the brachiopod Atrypoidea suggests somewhat turbid conditions (Jones 1974, pp. 408-409). The fine grain size and scarcity of current indicators in the rubbly limestone may reflect relatively quiet-water conditions. Most fossils of sedentary benthic organisms are still in life position, and the majority of the brachiopods are articulated. These features suggest a predominantly quiet-water environment,

well below wave base, a view supported by the fragile reef-builders and very fine-grained reef matrices. Storm-deposited shelly limestones and dislodged reef blocks are evidence of periodic higher energy levels, and may indicate deposition above storm wave-base.

Clastic limestone units in non-reefal intervals throughout the Douro Formation contain abundant intraclasts and rarer oolites and oncolites in addition to shelly debris. In contrast, intraclasts are rare in clastic units throughout the reefal intervals; oolites and oncolites were not observed. Scarcity of these high-energy indicators from rocks of the reefal intervals suggest that the reefal strata were deposited under less turbulent conditions than were non-reefal deposits. Reef growth probably occurred during the two deepest stages of the Douro transgression (Part I).

Although the fossil composition of the Lower and Upper Reefs are broadly similar in equivalent stages of development (Text-figs. 17A,B), several important differences are evident, as follows:

1) Bryozoans and the brachiopod Stegerhynchus are more common in reefs of the Lower Zone, particularly in the crinoid-rich facies.
2) Branching and "organ-pipe" corals (Syringopora, Aulopora, fasciculate rugosans) are more common in the Lower Reefs.

3) Heliolites, Alveolites, dish-shaped mucophyllids, lamellar and tabular coral colonies (all genera) and stromatoporoids are more common in reefs of the Upper Zone.

4) Calcareous algae are more common in crinoid-rich facies of the Upper Reefs and in coral-rich facies of the Lower Reefs.

5) Major fossil groups are commonly represented by different genera or species in reefs of the two zones.

The two reefal zones are both of Ludlow age, and are separated by only about 100 m of strata. Most of the reefal fossils range throughout the Ludlow, and many range through the entire Silurian. For these reasons, evolution of reefal organisms cannot be regarded as the major cause of differences in fossil composition between the two reefal intervals. It is more likely that reefs of the two intervals grew under slightly different paleoenvironmental conditions.

Similar floral, faunal and lithologic successions in reefal deposits (Text-figs. 17A,B) and similar sedimentary features (e.g. grain size, degree of fossil breakage, sedimentary structures) in inter-reefal deposits, suggest that there were no significant differences in depth or water turbulence between the two reefal intervals. However, the amount of terrigenous detritus suspended in the water may have had an influence on the faunal composition of the mounds.

Terrigenous clay and silt constitute 15-50% of inter-reefal strata of the Lower Zone, but less than 20% of equivalent strata of the Upper Zone. Organisms typical of argillaceous carbonates, such as bryozoans (Duncan 1957, pp. 784-785; Manten 1971, p. 427), branching and "organ-pipe" corals (Copper 1974, p. 381) and rounded coral colonies (Manten 1971, pp. 430-432; and references therein), occur more commonly in the Lower Reefs, whereas organisms typical of relatively pure carbonates, such as stromatoporoids (Manten 1971, pp. 438-439; Heckel 1972, p. 283) and flat coral (Manten 1971, pp. 430-432) occur more commonly in the Upper Reefs. The predominance of conical sponges and mucophyllids in the Lower Reefs in contrast to dish-shaped and lamellar forms in the Upper Reefs may reflect attempts to expose minimum surface areas during deposition of terrigenous detritus. Lower turbidity during formation of the Upper Reefs would have resulted in increased illumination, favouring the growth of red algae (Pseudochaetetes) in the Crinoid Stage. These evidences suggest that the amount of terrigenous detritus was a major influence on the faunal and floral composition of the two reefal zones.

Topographic Development

The sharp boundaries between massive mudstone cores and rubbly bioclastic haloes indicate an abrupt change in sedimentary environment, suggesting that the reefs were at least

slightly elevated above the sea floor. The presence of storm-dislodged reefal blocks in inter-reef channel deposits indicates that the reefs were elevated above the sea floor.

Scoffin (1971, pp. 194-198) has shown that the original morphology of reef surfaces can be determined through study of the angular relationships between geopetals and the bases of thin, in situ, tabular organisms (cf. Pl. 6, fig. 1). The utility of this method in the present study is limited somewhat by the abundant occurrence of tabular corals and stromatoporoids only in the uppermost parts of the reefs. Scattered observations within the uppermost 3 m of a reef suggests that the growth surface was convex, with dips averaging 30-40° at the margins. The centre of the reef had highly irregular relief, with decimetre- to metre-sized knobs and hollows.

Argillaceous seams of primary origin pass into and through the reefs. Uniformity of lithology throughout the main mass of the reefs suggests that any post-depositional compaction would have been uniform. The bases of argillaceous seams should therefore parallel the original growth surfaces of the reefs. Several argillaceous seams pass through the reef shown in plate 7B, providing an opportunity to observe successive growth stages. The lower seams are straight to gently convex with a maximum relief of considerably less than 1 m. The upper seams are irregularly convex and exhibit up

to 3 m of relief. This suggests that topographic relief increased during the growth of the reef.

Synthesis of the evidence of original topographic relief suggests that the reefs were relatively low structures, with a maximum relief of about 3 m above the sea floor. The delicate nature of most reef builders (especially the sponges), the mudstone matrix of the reefs and the absence of steeply dipping flank beds indicate that the reefs were not exposed to sustained vigorous wave activity. They should therefore be classified as stratigraphic reefs (Duncan 1970) or reef mounds (James 1978) rather than as ecologic reefs.

Formation of Reefal Mudstone

Petrographic studies of lime mudstone are hindered by the very fine grain-size of the particles and their common aggradation to microspar. As a consequence, the origin of the matrix of many mudstone mounds remains uncertain. Suggested origins include the baffling of inter-reefal mud (Wilson 1975, pp. 165-167), the disintegration of calcified algae (Laudon and Bowsher 1941), the breakdown of skeletal carbonates by boring organisms (Klement and Toomey 1967) and the precipitation of micrite cements (Mountjoy and Jull 1978).

The presence of disseminated terrigenous clay in the mudstone of the Douro sponge reefs indicates that at least some of the reefal matrix was derived from non-reefal sources.

It is likely that reefal organisms such as sponges, crinoids and branching corals baffled weak currents and caused deposition of argillaceous lime mud on the reefs. However reefal mudstones contain considerably less terrigenous material than is present in inter-reef deposits, suggesting that much of the lime mud was produced on the reefs (cf. Petta and Gerhard 1977).

This conclusion is supported by preservational characters of the sponges. The spaces between the spicules are consistently completely infilled with lime mud (Pl. 5; Pl. 8), but several features of this fill suggest that passive settling of sediment can account for only a small fraction of the material. Mudstone between the spicules generally contains less argillaceous and fine shelly debris than does the mudstone surrounding the sponges. Although infill between the spicules was virtually complete, commonly the larger areas between the tubes of Syringopora (Pl. 4, fig. 2) or even within the central cavities of sponges (Pl. 4, fig. 1) were not completely infilled. These features are not typical of passive infill, and suggest pervasive formation of micrite between the sponge spicules.

Microscopic examination of micrite in the interspicular mudstone reveals patches of numerous, very poorly preserved tubules which resemble the alga Girvanella (B. Mamet, pers. comm., 1980). Girvanella represents a blue-green alga in which the filaments are internally and externally calcified

with micrite (Riding 1977). Growth and calcification of the filaments is very rapid, and thus could result in the production of large volumes of lime mud (Schroeder 1972; Kobluk and Risk 1977). The disintegration of Girvanella tubules could have formed significant amounts of lime mud in the Douro Sponge Reefs. Alternatively, the lime mud may have been formed through inorganic precipitation of micritic cements between the spicules.

The spicules of modern lithistid sponges are composed of opaline silica (de Laubenfels 1955, p. E34; Hartman 1980, p. 28). The spicules of many fossil lithistids are presently composed of quartz or chert (cf. Toomey and Nitecki 1979). However, detailed petrographic examinations reveal that virtually no primary spicular material is present in the Douro Sponge Reefs; the spicules have been dissolved and the voids later infilled with sparry calcite. Little evidence of the original sponge composition of the mounds might remain if the spicules had not been molded by the micrite. In addition, spicules are not visible in patches where the micrite has undergone even slight dolomitization.

Siliceous spicules are unstable in most modern reefal environments, and are rapidly dissolved. Dissolution is apparently most pronounced under conditions of rapid carbonate deposition and synsedimentary cementation (Macintyre 1977, pp. 510-511; Rützler and Macintyre 1978, p. 149;

Wiedenmayer 1980a, pp. 108-109). Although siliceous sponges are common in modern reefs, their spicules are rarely preserved (Land 1976; Hartman 1977). Early dissolution of silica and late diagenetic alteration of spicular limestones has probably resulted in sponges being under-represented as fossils in many ancient reefs. Indeed, sponges may have played a significant role in the construction of many of the enigmatic "unfossiliferous" mud mounds common throughout the Phanerozoic record.

Diagenesis

Small shelter cavities commonly formed beneath or within skeletons in the Douro Sponge Reefs (Pl. 4, figs. 1-3). Cavities formed by the collapse or dissolution of sponges were considerably rarer. The pelleted floor deposits may have resulted from cementation processes (Macintyre 1977) or the excretion of fecal pellets.

Larger, more irregularly shaped cavities exhibit scalloped walls and ceilings that smoothly truncate skeletal fragments (Pl. 4, figs. 4-6). The absence of solution features suggests that these cavities were formed by macroboring invertebrates which reduced skeletal material and lithified mudstone to silt-sized fragments. The borings and resultant fragments are broadly similar in size and morphology to those produced by Recent acrociid sponges (cf. Rützler 1971; Warme 1975, p. 199), but the scarcity of information on Paleozoic sponge borings (cf. Bromley 1970, p. 77) makes direct comparisons difficult.

Several features of the reefal mudstone suggest that it underwent synsedimentary lithification. Dislodged blocks of reefal mudstone in channels, and cavities which remained open despite compaction, both indicate that the mudstone had considerable internal cohesion. Cements are commonly substrate specific (James et al. 1976; Longman 1980); the restriction of generation 1 to skeletal material and the roofs of cavities can be explained as a restriction to lithified substrates. Biogenic excavations in reefal mudstone smoothly truncate skeletal fragments, suggesting that cavity roofs and skeletal material were similar in consistency, and therefore both lithified. By analogy with recent reefs (James et al. 1976) it is likely that the fine-grained matrix of the reefs was cemented by micrite.

Comparison with other sequences of cements (James and Kobluk 1979; Longman 1980; and references therein) suggests that all three generations of cavity-filling cement precipitated from meteoric waters. Generation 1 probably formed under meteoric vadose (freshwater, subaerial) conditions whereas generation 3 formed under meteoric phreatic (freshwater, below the water table) conditions. The environment in which generation 2 crystals precipitated is more problematic, but this generation was apparently transitional.

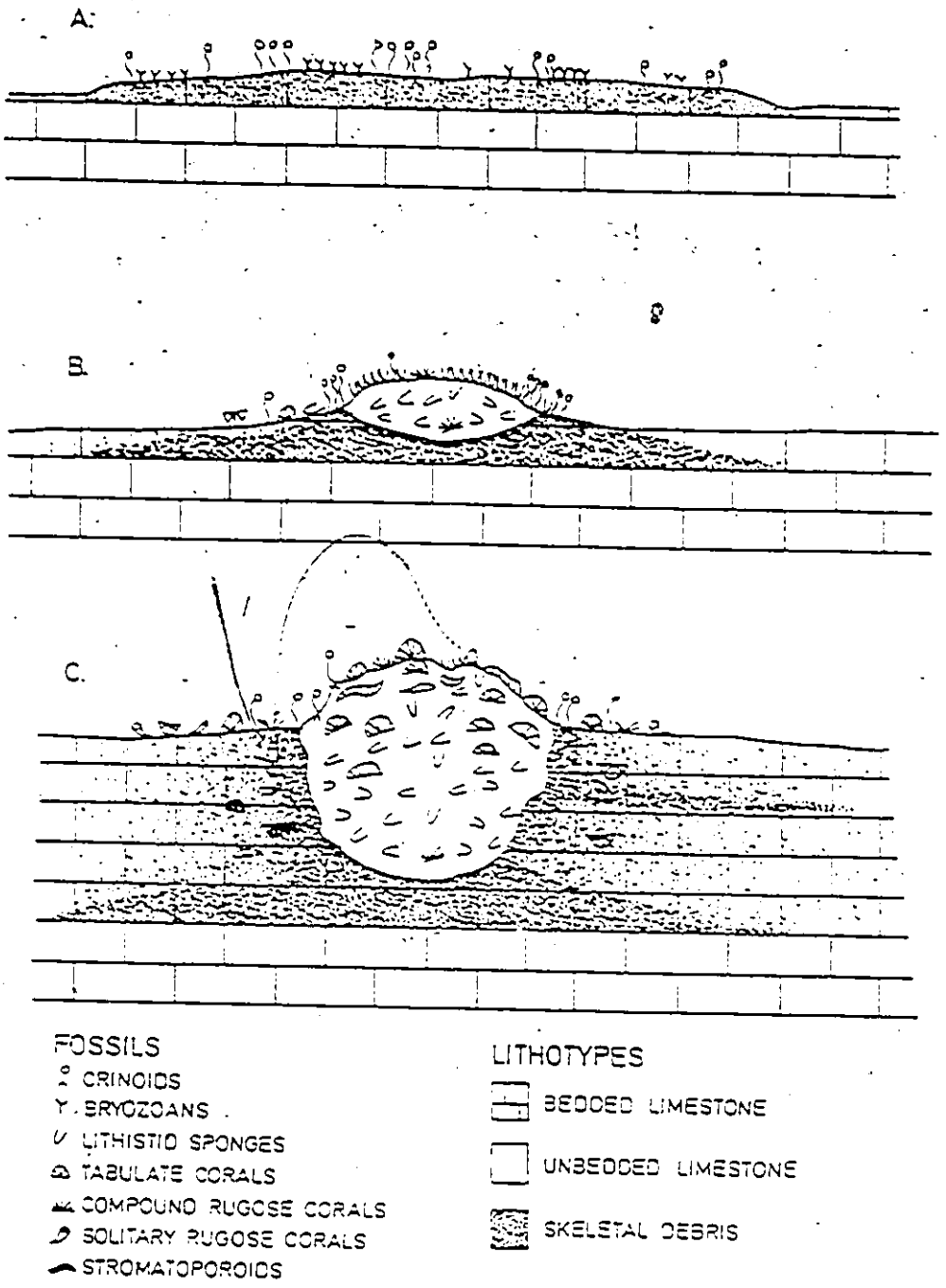
between the other two, and hence probably formed in an intermediate environment, possibly near the vadose-phreatic interface.

Fracturing probably accompanied precipitation of generation 2 crystals; pressure solution followed precipitation of generation 3.

Growth Stages

The occurrence of similar lithologic and paleontologic sequences in all reefs examined suggests that the Douro Sponge Reefs of both zones passed through similar developmental stages. The ideal succession common to both zones appears to involve three stages in which crinoids, sponges and corals predominated in turn.

In the initial Crinoid Stage of reefal development (Text-fig. 18A) crinoids, bryozoans and (locally) solenoporoid algae stabilized and accentuated an accumulation of bioclastic debris. Of these, the most important were the crinoids: they baffled sediment with their stems, bound sediment with their holdfasts, and produced large volumes of sand- to gravel-sized sediment upon death and disarticulation. This produced a low mound with a maximum topographic relief of a few decimetres.



Text-fig. 18. Stages in the development of the Douro Sponge Reefs.

A. Crinoid Stage
B. Sponge Stage
C. Coral Stage

The succeeding Sponge Stage began when numerous lithistid sponges colonized an area near the centre of the mound of crinoidal debris (Text-fig. 18B). They baffled argillaceous lime mud transported from inter-reef areas; lime mud was also produced on the reef. A few corals functioned as frame builders and bafflers; bryozoans and calcareous algae functioned mainly as binders. Crinoids growing near the margins of the reef contributed to the development of an irregular halo of bioclastic debris. Diversity was more than twice that of the Crinoid Stage, and topographic relief had increased to about one metre. The lime mud matrix was lithified by micrite-sized cement, and cavities were enlarged by boring organisms. Storm-generated waves intermittently dislodged reef organisms and blocks of reef-rock and transported them into inter-reef channels.

With continued growth of the reef, corals gradually became more prevalent and produced the culminating Coral Stage (Text-fig. 18C). Sponges, calcareous algae, bryozoans and stromatoporoids were locally common; species and growth form diversity of reef builders and dwellers reached an acme. The matrix of lime mud rich in skeletal fragments was subject to processes of synsedimentary lithification, bioerosion and storm-erosion. Topographic relief increased to a maximum of about 3 metres.

Walker and Alberstadt (1975) suggested that reefs of all ages pass through four basic stages of development, which they termed the stabilization, colonization, diversification and domination stages. James (1978) confirmed the general applicability of this model, but showed how evolutionary and environmental factors could result in stages being absent or poorly developed.

The stabilization (pioneer) stage most commonly consists of an accumulation of skeletal debris bound by rooted organisms or algae. In the Douro Sponge Reefs, it is represented by the Crinoid Stage. The colonization stage, composed of unbedded mudstone-wackestone with numerous delicate baffling and binding organisms, is represented by the Sponge Stage. The diversification stage, consisting of a diverse assemblage of organisms in a mudstone - wackestone matrix, is represented by the Coral Stage. The domination stage, consisting of a low diversity assemblage of lamellar and encrusting binders, is apparently not present in any of the Douro Reefs. The greater proportion of lamellar and encrusting corals and stromatoporoids at the tops of the Lower Reefs is broadly similar, but taxonomic diversity is unchanged and growth form diversity is even higher.

COMPARISONS

Silurian Reefs

The Douro Sponge Reefs are most similar in size and morphology to small, "patch reefs" such as the Wenlock Reefs of England (Scoffin 1971), the Upper Visby and Hoburgen reefs of Gotland (Manten 1971) and the Gasport Reefs of New York State (Crowley 1973). These reefs average less than 10 m in all dimensions, and are composed of mudstone or wackestone with abundant in situ fossils. Flanking deposits commonly contain abundant bioclastic material, but steeply dipping flank beds are absent. Core and flank deposits are generally quite distinct, but there is a greater amount of intercalation than is typical of the Douro Reefs. Cores of these reefs do not exhibit a consistent or well-developed lateral zonation. There is commonly a decrease in bioclast size away from reefs (e.g. Manten 1971, pp. 217-218), but similar analyses of fossil zonation have not been carried out. Maximum topographic relief was less than 3 m.

In contrast, the Douro Sponge Reefs show few similarities to the larger Niagaran reefs of the Great Lakes area (Shaver et al. 1978; and references therein) and Llandoverian reefs of North Greenland (Hurst 1980; and references therein). These reefs are up to 500 m thick and several kilometres wide, and exhibited a primary topographic relief of several tens of metres. Steeply dipping bioclastic flank beds extend from the mounds. In some reefs, distinct

concentric belts, each characterized by a different faunal group, occur around and within the central core; forereef and backreef facies can commonly be distinguished. The absence of these features from the Douro Sponge Reefs probably reflects their smaller size, lower topographic relief and less turbulent environments.

Although vertical zonation is not present in all Silurian reefs (Scoffin 1971; Manten 1971), it has been reported from the Gasport patch reefs (Crowley 1973), Michigan Basin pinnacle reefs (Mesolella et al. 1974; Huh et al. 1977) and the Niagaran reefs (Lowenstam 1957; Shaver 1974). The patch and pinnacle reefs rest on crinoidal deposits. An initial core facies, containing numerous delicate branching corals and encrusting algae, passes upwards into low diversity assemblages of stromatoporoids (Gasport reefs) or stromatoporoids and stromatolitic algae (Michigan Basin pinnacle reefs). Basal stages of a typical Niagaran reef consist of Favosites and Syringopora colonies growing on an accumulation of crinoidal debris. Faunal diversity, and the abundance of stromatoporoids, corals and reef dwellers increase upwards through the core whereas the abundance of sponges and stromatactis decreases.

The fauna of the Niagaran reefs and most smaller Silurian reefs is dominated by corals and/or stromatoporoids. In contrast, the Douro Reefs are dominated by sponges; corals

are common only in the uppermost facies. With the exception of the halysitids, all major groups of Silurian reef-building corals are present in the Douro Reefs, although most are considerably reduced in abundance and diversity.

Holocene Buildups

The Douro Sponge Reefs can be compared with two of the categories of western Atlantic Holocene buildups described by Ginsburg and James (1974). They are similar to both algal banks (Turmel and Swanson 1976) and patch reefs (Garrett et al. 1971; Jordan 1973; Scoffin and Garrett 1974; Jones 1977) in terms of their sheltered locations and relatively low topographic reliefs. Features more typical of algal banks include the scarcity of abraded skeletal material in the reefs and the growth forms of the corals; features more typical of patch reefs include their sizes, their steep and sharp margins and the associated haloes and channel-fills of bioclastic debris. Lower Paleozoic reefs commonly exhibit a combination of features typical of banks and patch reefs (Scoffin 1971; Abbott 1975; James and Kobluk 1979).

Perhaps the closest Recent analogues are the sponge reefs growing on the Great Bahama Bank (Bliefnick and Gebelein 1978; Wiedenmayer 1978, 1980d). These occur in a narrow belt within the subtidal grapestone facies, well back from the shelf margin. They are 1 to 5 m in diameter and generally less than 0.5 m high, although relief rarely attains 3 m. The most common

reefal organisms are demosponges, green algae and alcyonarian corals. Sponges dominate the lower portions of the reefs, but corals dominate the upper parts. Reef matrix comprises silt- to sand-sized carbonates cemented by acicular and micritic aragonite. Both matrix and skeletons are extensively bored.

Sponge Reefs Through Time

The major occurrences of sponge reefs in the geologic record are summarized in Table 4. Sponge-dominated reefs have also been reported from Pennsylvanian and Triassic strata (Rigby 1971; Wendt 1980b; and references therein), but insufficient information is available on these occurrences.

With the exceptions of some Jurassic and Permian reefs, sponge reefs tend to be relatively small structures; most are less than 10 m in all dimensions. The matrix is generally mudstone or wackestone. Sponges occur most commonly in facies representing relatively tranquil environments; even the massive sclerosponges of modern Jamaican reefs occur most commonly in deep forereef deposits.

It seems likely that sponges filled the ecologic niche of corals as reef builders during geologic periods in which coral diversity was low (Finks and Toomey 1967, pp. 96-97). During these periods sponge reefs had a global distribution,

Age	Early-Middle Ordovician	Late Silurian	Permian	Jurassic	Holocene
Locations	Southwest U.S.A. Newfoundland Alberta New York State	Arctic Canada	Southwest U.S.A. Tunisia Germany	Germany Nova Scotia Basin Morocco	Bahama Bank
Global Coral Diversity	Low	High	Low	Moderate	High
Paleogeographic Setting	Platform and Platform Margin	Platform	Platform, Platform Margin and Basin	Basin	Platform
Average Reef Thickness	< 5 m	10 m	< 1 m to > 100 m	> 100 m	< 5 m
Reef Matrix	Wackestone	Mudstone to Wackestone	Wackestone	Mudstone	Wackestone to Packstone
Vertical Zonation	Early Ord.: Inconsistent Middle Ordovician: Sponges + Stromatoporoids and Corals	Sponges + Corals	Inconsistent	Absent or Sponges + Corals	Sponges + Corals

Table 4. Comparisons of sponge mounds through time. Data sources as follows: Early Ordovician (Wilson 1975, p. 97-98; Toomey and Nitecki 1979, p. 151-157; and references therein), Middle Ordovician (Pitcher 1964; Finks and Toomey 1969), Late Silurian (Narbonne and Dixon 1978; this study), Permian (Rigby 1971; Toomey and Cys 1979; Wiedenmayer 1980b; Wendt 1980a; and references therein), Jurassic (Gwinner 1976; Eliuk 1978; Wiedenmayer 1980c; and references therein), Holocene (Bliefnick and Gebelein 1978; Wiedenmayer 1978, 1980d).

and formed in platformal, platform marginal and basinal settings. Sponges commonly occurred throughout all stages of reefal development, including climax stages. These reefs were similar to Early Cambrian archeocyathid reefs in that they lacked massive, hemispherical framebuilders, and hence could not become wave resistant (James and Kobluk 1979).

Sponge reefs also occurred, albeit rarely, during geologic periods in which coral faunas were more diverse (e.g. Late Silurian, Jurassic, Holocene). During these periods coral reefs were common, especially in platform marginal settings, whereas sponge reefs formed rarely, mainly in platformal and basinal settings. Sponges occurred throughout many of the basinal Jurassic reefs; in Silurian, Holocene and some basinal Jurassic sponge reefs, sponges were common in early stages of reefal development but were generally replaced by corals in climax stages.

Synthesis

Throughout the Phanerozoic, sponges and corals have generally tended to mutual exclusion (Finks 1970). Sponges were probably less efficient competitors in reefal environments than were corals and other typical reef builders (Finks and Toomey 1969, p. 97), and hence played significant roles in reefal construction only in situations in which the usual

reef builders were restricted or excluded, either by evolutionary decline in one of the groups or by environmental conditions unfavourable to the growth of normal reef builders (Heckel 1974, p. 124).

Evolutionary restriction can be ruled out in the case of these Upper Silurian sponge reefs, as the corals and stromatoporoids were near an evolutionary acme (Heckel 1974; Copper 1974). It is also very unlikely that corals were excluded by extremely unfavourable environmental conditions. The Douro Sponge Reefs grew between wave-base and storm wave-base in warm marine waters of normal or near-normal salinity, conditions which did not differ markedly from those of most Silurian coral-stromatoporoid reefs. In addition, both corals and sponges occur in all reefal and inter-reefal facies, indicating that neither was strictly excluded from any of the micro-environments.

It is most likely that, as in the case of the Recent Bahamian sponge reefs (Bliefnick and Gebelein 1978; Wiedenmayer 1978, 1980d), a combination of subtle environmental variables favoured the growth of sponges over that of corals in the initial stages of reef growth. Three interrelated factors which may account for this are:

1) Paleogeography. Recent sponge reefs occur in platformal settings rather than in the platform marginal settings typical of coralgal ecologic reefs.

Similarly, the Douro Reefs grew on the platform, more than 100 km from the platform margin. Silurian platform marginal buildups are predominantly composed of corals and stromatoporoids, whereas those of the platform are more variable in composition with local development of crinoidal, bryozoan or algal reefs (Wilson 1975, pp. 107-112).

2) Substrate. Sponges grow on lithified, firm and even some soft substrates whereas colonial corals prefer lithified substrates or skeletal fragments for larval attachment (Heckel 1972, pp. 248-249). In the Douro Reefs, sponges characterize mudstone facies whereas corals characterize most wackestone facies.

3) Growth Requirements. Studies of the feeding mechanisms of modern demosponges (Reiswig 1971) and a Recent zoned coral-sponge patch reef (Bonem and Stanley 1977) suggest that, at present, the growth of sponges is favoured over that of corals in relatively calm, turbid, nutrient-poor or light-deficient environments. Paleontologic and sedimentologic evidences suggest that the Douro sponge faunas flourished under calm, turbid conditions. The nutrient and light levels are more difficult to determine, but these are commonly low in initial stages of reefal development, particularly in turbid environments.

It is unlikely that any single environmental factor was solely responsible for the unique sponge development of the Douro Reefs. More likely the platformal setting, muddy substrate, high turbidity, low water turbulence and other related factors combined to favour the growth of sponges over that of corals in early stages of reefal development.

However, many of these factors changed during the growth of the reefs. Increased topographic relief probably increased turbulence, circulation and illumination, and may have decreased the effects of bottom turbidity. The lime mud substrate became progressively richer in skeletal debris. All of these changes would increasingly favour the growth of corals over that of sponges. For these reasons, the sponge colonization community was gradually replaced by a more diverse assemblage of corals and stromatoporoids.

The upwards replacement of a sponge colonization community by a coral diversification community has been reported from Ordovician, Silurian, Jurassic and Holocene sponge reefs (Table 4). Sponges commonly functioned as initial reef colonizers in situations in which evolutionary or environmental factors restricted branching corals, bryozoans and other common colonizers. Reefal development resulted in physical and biological changes in the environment which generally tended to favour the growth of frame building corals and stromatoporoids over that of sponges. Only under conditions

of extreme evolutionary or environmental coral restriction (e.g. Early Ordovician-worldwide; Late Jurassic-deepwater basins) were sponges able to flourish in all stages of reefal development.

CONCLUSIONS

1) Sponge reefs occur abundantly in two zones within the Upper Silurian (Ludlovian) Douro Formation on Somerset Island, Arctic Canada. They are the first reported Silurian reefs constructed predominantly by sponges.

2) The reefs are relatively small (5-35 m in diameter), predominantly subspherical structures composed of unbedded, richly fossiliferous mudstone and wackestone. Each reef is underlain by a lensoid to tabular body of crinoidal packstone, and is surrounded by an irregular halo of crinoidal wackestone. Wedges and channel-fills of crinoidal packstone extend from the reef into the inter-reefal rubbly mudstone.

3) Lateral zonation is not well developed within the reefs. However, the proportion and average size of skeletal debris in reef haloes decreases with distance from the reefs. The abundance and diversity of all fossil groups, especially reef builders, also decreases away from the reefs. The influence of the reefs on the surrounding deposits was negligible at distances of more than 15 m from their margins.

4) Vertical zonation is well developed. The basal reef facies is a thin lens of bedded crinoidal packstone with abundant cirriferous crinoid holdfasts and local concentrations of bryozoans, solenoporid algae and rhynchonellid brachiopods. This is overlain abruptly by unbedded sponge-rich mudstone which forms the major part of the reef. Towards the top of the reef, this facies passes into crinoidal wackestone with abundant corals; calcareous algae and sponges are also locally common. This zonation corresponds closely to the stabilization, colonization and diversification stages of Walker and Alberstadt (1975).

5) Reef growth probably occurred in calm, turbid, tropical, marine shelf environments. Concentrations of terrigenous mud restricted the abundance and average size of the reefs, and resulted in changes in their biotic composition.

6) Orientations of both in situ tabular organisms and seams of mechanically deposited clay suggest that topographic relief increased to about 3 m during the growth of the reefs. However, the delicate nature of the fossils, mudstone matrices and absence of steeply dipping flank beds indicate that the reefs were not wave resistant.

7) Some of the mudstone matrix was transported from non-reefal areas, but a large amount was produced on the mounds, possibly by breakdown of algal tubules

or inorganic precipitation of micritic cement. The originally siliceous spicules of the lithistid sponges were dissolved and the voids infilled with sparry calcite. Pervasive formation of inter-spicular micrite apparently played an important role in sponge preservation. Early dissolution of sponges is common in reefal environments, and may have resulted in the under-representation of sponges in many fossil reefs.

8) The presence of dislodged blocks of reefal mudstone in inter-reef beds, reefal cavities which remained open throughout compaction, and probable invertebrate borings in mudstone suggest synsedimentary cementation of the reefs, probably by micritic Mg-calcite. Fabrics and compositions of sparry calcites in cavities record three generations of meteoric cementation.

9) The Douro Sponge Reefs are similar in structure to small Silurian "patch reefs", but show few similarities to the larger Niagaran reefs. They exhibit features typical of both algal banks and patch reefs of the western Atlantic, but their closest Holocene analogues are small sponge reefs growing on the Great Bahama Bank.

10) During geologic periods in which normal reef builders (corals, stromatoporoids and coralline algae) were in evolutionary decline, sponge reefs were geographically and environmentally widespread, and sponges commonly

played significant constructional roles throughout the reefs. In contrast, during periods in which the normal reef builders were diverse, sponge reefs were rare and environmentally restricted; sponges occurred mainly in colonization communities during early stages of reefal development.

PART III

TRACE FOSSILS FROM UPPER SILURIAN TIDAL FLAT TO BASIN SLOPE CARBONATES, SOUTHEASTERN CANADIAN ARCTIC ISLANDS

TRACE FOSSILS FROM UPPER SILURIAN TIDAL FLAT TO BASIN SLOPE CARBONATES, SOUTHEASTERN CANADIAN ARCTIC ISLANDS

Abstract. Ludlovian carbonates on Somerset, Cornwallis and Devon Islands contain numerous trace fossils. A *Polarichnus-Bergaueria* association characterizes limestones and dolostones deposited in the intertidal zone (Cape Storm and Leopold Formations), a *Fuersichnus-Uchirites* association characterizes limestones deposited under shallow subtidal conditions (Douro Formation), and a *Scalarituba* association characterizes basin slope limestones (tongue of ?Cape Phillips Formation).

Trace fossils in planar-bedded calcisiltite and dolosiltite were preserved through toponomic processes, which resulted in diverse ichnocoenoses similar to those reported from contemporaneous shallow marine siliciclastic rocks. In contrast, trace fossils in bathymetrically equivalent rubbly (nodular) calcilutite were preserved through diagenetic processes, which resulted in ichnocoenoses largely restricted to infaunal feeding and dwelling traces. Although the mineralogic composition of the substrate is probably relatively unimportant in controlling the distribution of trace-making organisms, the

greater susceptibility of carbonates to early and late diagenetic processes can significantly affect the nature of the ichnocoenose.

Details of the formation and preservation of trace fossils suggest that the calcilutite substrates were generally firm, whereas calcisiltite substrates ranged from firm to thixotropic. Simple, "non-diagnostic" burrows such as Palaeophycus can contribute a wealth of information on substrate consistency, much of it not readily available from more traditional environmental indicators.

The trace fossils can be attributed primarily to the activities of worms, trilobites and sea anemones. Twenty-seven species and forms are described, including the new species Fuersichnus douroensis, Helicodromites arctatus, Uchirites ascendens and U. ramosus. Fuersichnus, Helicodromites, Laminites and Uchirites are herein reported for the first time from Lower Paleozoic strata.

INTRODUCTION

Studies of both fossil and recent traces have repeatedly demonstrated their value as environmental indicators. Trace fossils can yield important information on a variety of paleoenvironmental factors including bathymetry, substrate consistency, sedimentation rates, salinity, oxygen levels and degree of water agitation (Seilacher 1964; Rhoads 1975). Characteristics of ichnofossils which make them especially useful in paleoecology include their broad time ranges, narrow facies ranges, lack of secondary transport and common enhancement by diagenetic alteration (Seilacher 1964, p. 301).

Most ichnologic studies have been based on siliciclastic sequences, particularly alternating sandy and shaly beds, in which abundant, well preserved traces are commonly the only fossils present. In contrast, trace fossils in carbonates are generally inconspicuous and difficult to study, and are commonly overlooked because of the abundance of body fossils (Frey 1970, p. 10). Although detailed ichnologic studies have contributed to an understanding of the depositional and diagenetic histories of some Mesozoic carbonates (e.g. Bromley 1967; Kennedy 1967, 1970; Frey 1970; Ward and Lewis 1975), the ichnology of Lower Paleozoic carbonates has been relatively little studied (Kennedy 1975, p. 378). Some individual ichnospecies have been discussed in detail (e.g. Palmer 1978;

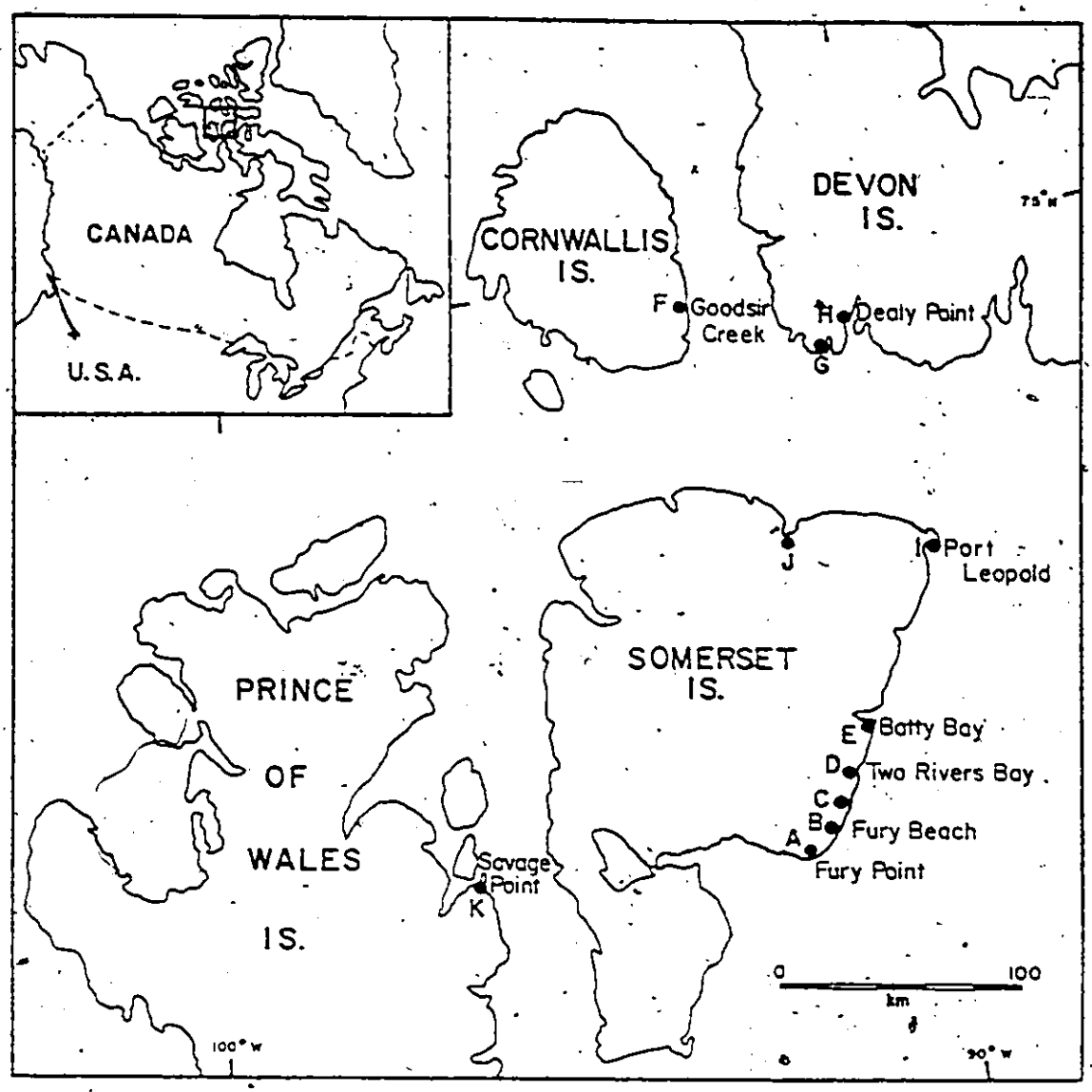
Pickerill and Forbes 1977, 1978; Narbonne et al. 1979) and trace fossil evidence has been incorporated in several sedimentologic and paleoecologic studies (e.g. Braun and Friedman 1969; Walker and Laporte 1970; Byers and Stasko 1978; Jones et al. 1979), but two studies of Ordovician limestones (Osgood 1970; Pickerill and Forbes 1979) represent the only detailed ichnologic studies of Lower Paleozoic carbonates to date.

The present study is the first comprehensive and detailed examination of an ichnocoenose from Silurian carbonates. In addition, although trace fossils have been mentioned in various regional geologic reports (e.g. Trettin 1975, 1978) and several new forms have been named (Ami 1906; Narbonne et al. 1979), no systematic study of an entire ichnocoenose from Arctic Canada has been previously published.

METHODS AND TERMINOLOGY

Strata in the study area are superbly exposed on high sea-cliffs and in deep river gorges. Detailed sections were measured on southeastern Somerset and Cornwallis Islands (Text-fig. 19, localities A-F). Sections were divided on the basis of lithology and contained body fossils into field units averaging one metre in thickness. All observed trace fossils were collected or carefully recorded in the field. Subsequently, a large hand sample from each unit was cut, polished, gently etched and stained with Alizarin Red-S (cf. Friedman 1959), and this revealed numerous otherwise obscure trace fossils. Specimens obtained from reconnaissance sections on southwestern Devon Island (Text-fig. 19, loc. G-H), and from the University of Ottawa collections of Dr. O.A. Dixon from northern Somerset and eastern Prince of Wales Islands (Text-fig. 19, loc. I-K) are also incorporated in this manuscript.

In this paper, the term assemblage is used for a group of trace fossils which occurs consistently in one subfacies or lithology within an environmental zone. An association comprises all trace fossils within an environmental zone, and commonly consists of several assemblages. Ichnofacies is a term coined by Seilacher (1964) for a trace fossil association which has a global distribution and recurs throughout the Phanerozoic. Terminology follows Seilacher (1964) and



Text-fig. 19: Geographic location of sample sites.

Martinsson (1970) for toponomy, Simpson (1975, table 3.4) for mode of preservation, and Osgood (1970, pp. 314-315, 351) for U-shaped burrows and arthropod tracks.

STRATIGRAPHIC AND PALEOENVIRONMENTAL SETTING

All strata considered in this study were formerly regarded as part of the Read Bay Formation of Thorsteinsson and Fortier (1954), but recent studies have indicated that this unit comprises several mappable formations (Part I; and references therein). The Douro Formation (Thorsteinsson 1963), the principal unit of this study, is composed predominantly of fossiliferous rubbly (nodular) limestones. The upper half of the Douro Formation on Somerset Island is laterally equivalent to blocky-weathering limestone and shale on eastern Cornwallis Island; these blocky-weathering strata probably represent a tongue of the Cape Phillips Formation. On eastern Somerset Island, the Douro Formation is underlain by the Leopold Formation (Jones and Dixon 1975), whereas on other islands it is underlain by the Cape Storm Formation (Kerr 1975). Both of these formations are composed predominantly of planar-bedded dolostone and limestone, but can be distinguished by the greater proportion of detrital, evaporitic and stromatolitic units in the Leopold Formation (Dixon and Jones 1978, p. 422). All strata considered in this study are Ludlovian in age (Part I; and references therein).

The strata in this study were deposited during a major transgression, and record a variety of environments ranging from high intertidal to basin slope. Strata on southern Somerset and Devon Islands accumulated on a broad, shallow carbonate shelf, while those on Cornwallis Island were near the shelf margin.

The lowest strata of the Leopold Formation exposed in the measured sections, the planar-bedded dolosiltite and sandstone of the Cape Clarence Member (Pl. 10, fig. 1), were deposited in intertidal environments (Dixon and Jones 1978). The overlying Prince Leopold Member is composed of planar-bedded dolosiltite, calcisiltite and sandstone, deposited under low intertidal conditions, interbedded with minor rubbly and biostromal limestones deposited under shallow subtidal conditions (Dixon and Jones 1978). The upper part of the Cape Storm Formation on eastern Cornwallis Island similarly consists of planar-bedded dolosiltite and calcisiltite interbedded with rubbly and biostromal limestones, and was also deposited under alternating low intertidal-shallow subtidal conditions (Gibling and Narbonne 1977, pp. 1148-1149). The upper part of the Cape Storm Formation on Devon Island consists predominantly of dolosiltite and calcisiltite, and was probably deposited under mainly intertidal conditions (Mayr 1978, p. 20).

Plate 10

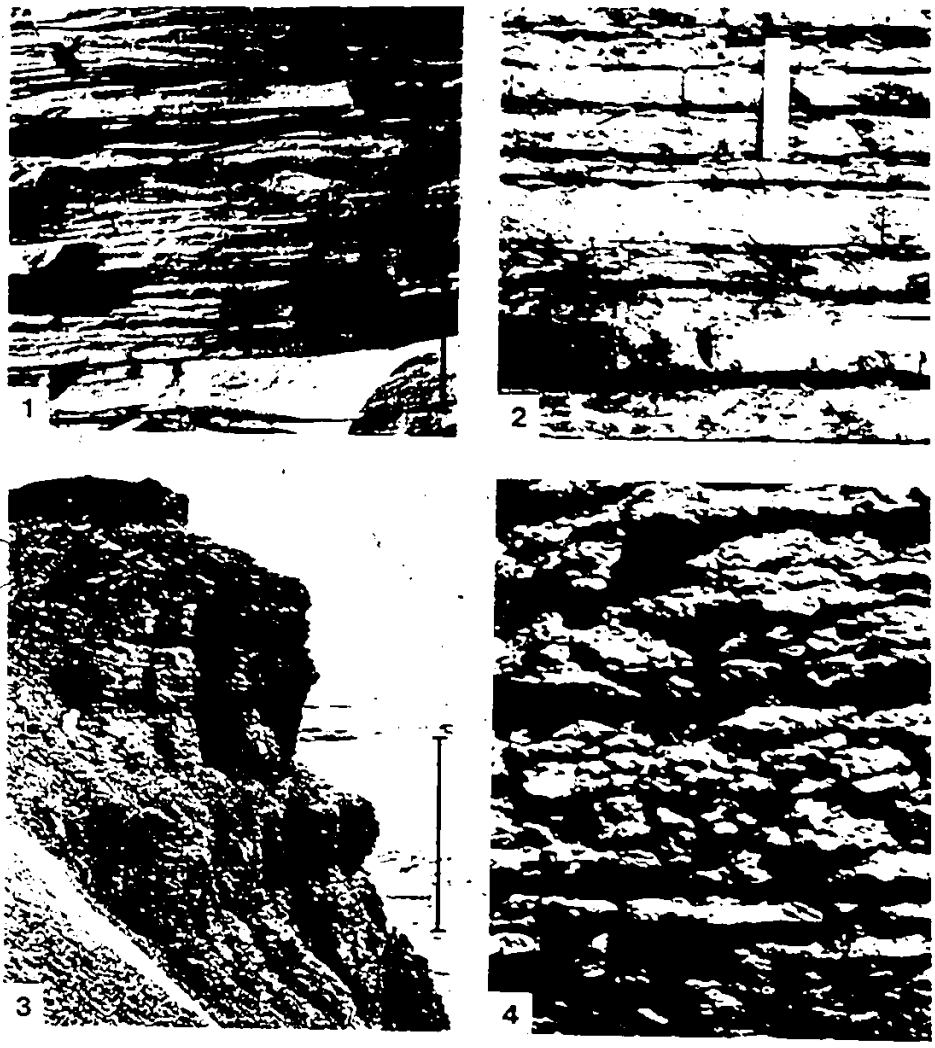
Field appearance of typical trace-bearing lithotypes.

Fig. 1. Planar-bedded, ripple-marked sandy calcisiltite and calcareous sandstone. Cape Clarence Member of Leopold Formation. Scale bar represents 15 cm. Photo by O.A. Dixon.

Fig. 2. Planar-bedded calcilutite and shale. Tongue of ?Cape Phillips Formation. Ruler is 15 cm long. Photo by J.F. Packard.

Fig. 3. Rubbly calcilutite. Douro Formation. Scale bar represents 3 m.

Fig. 4. Rubbly calcilutite with three planar beds of calcisiltite. Douro Formation. Ruler is 15 cm long. Photo by J.J. Packard.



PI. 10

The Douro Formation is composed largely of fossiliferous rubbly calcilutite with interbeds of calcisiltite, calcarenite and calcirudite (Pl. 10, figs. 3,4), and was deposited in subtidal shelf environments above storm wave-base (Jones and Dixon 1976; Gibling and Narbonne 1977; Mayr 1978, pp. 21-22; Thomas and Narbonne 1979, p. 3). Relatively shallow subtidal shelf deposits (cf. Laporte 1971) are best developed in the lowermost 60 m of the formation. These are predominantly rubbly calcilutite interbedded with storm deposits consisting of erosionally-based units of planar-bedded intraclastic and shelly calcarenite and calcirudite; very thin (<0.1 m thick) storm deposits of calcisiltite with ripple cross-lamination, prod marks and megaripples occur sporadically. Somewhat deeper subtidal shelf deposits are predominantly rubbly calcilutite with storm deposits of shelly calcarenite and calcirudite. Inorganic sedimentary structures are very rare. Lithistid sponge bioherms of quiet water origin occur sporadically (Narbonne and Dixon 1978; Part II), and faunal diversity is greater than in the shallow subtidal deposits. The tongue of the ?Cape Phillips Formation on southeastern Cornwallis Island consists of very sparsely fossiliferous, thinly planar-bedded calcisiltite and calcilutite which is locally interbedded with black silty shale containing abundant monograptids (Pl. 10, fig. 2). These strata were

deposited below storm wave-base (Thomas and Narbonne 1979), and closely resemble peri-platformal slope deposits described by McIlreath and James (1978). The uppermost 10 m of these deposits contain an assemblage of body fossils similar to that of the deep subtidal shelf deposits, suggesting a return to shallower-water conditions near storm wave-base (Thomas and Narbonne 1979).

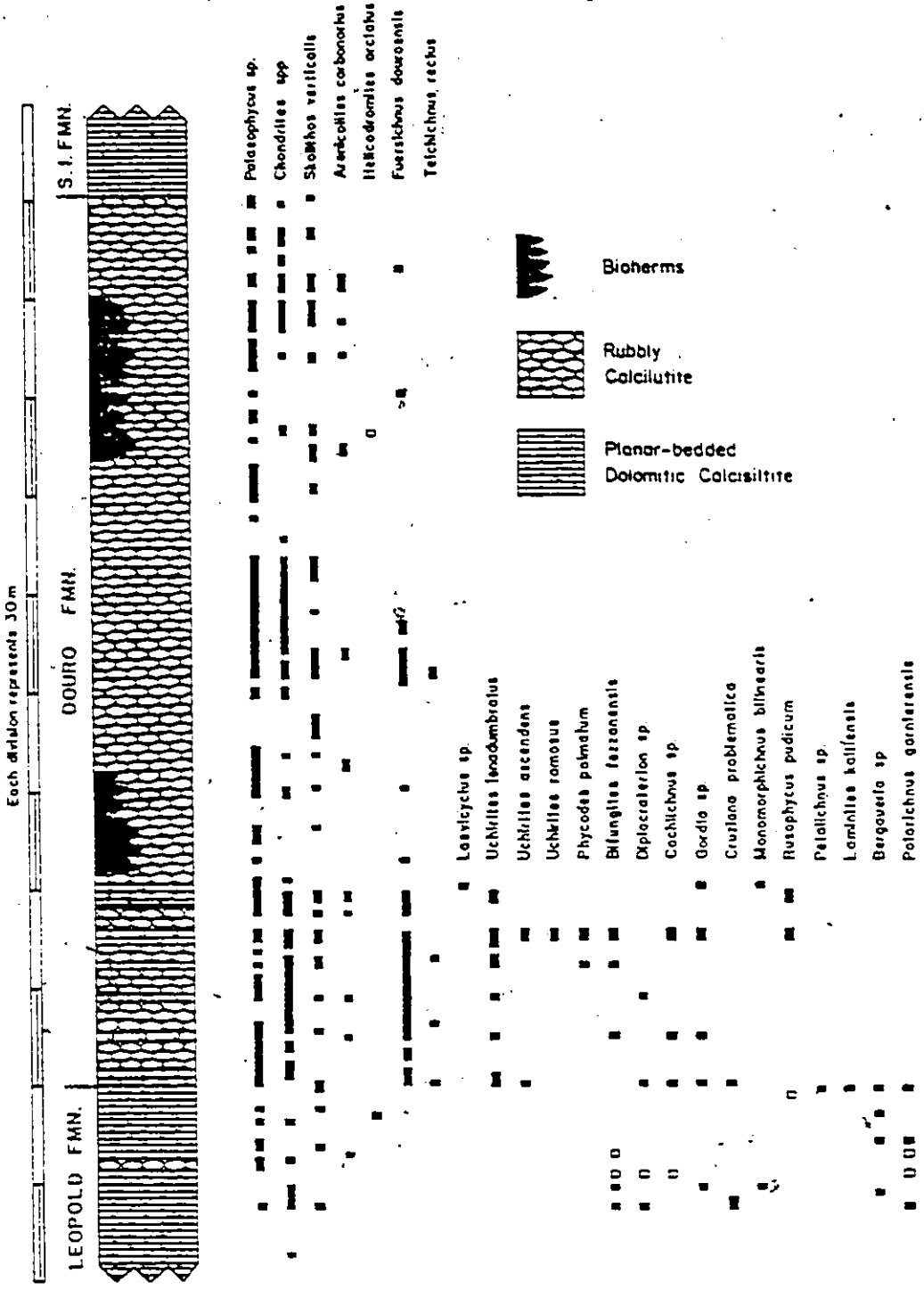
The distribution of trace fossils in the two main sections is shown in text-figures 20 and 21.

TRACE FOSSIL ASSOCIATIONS AND ENVIRONMENTS

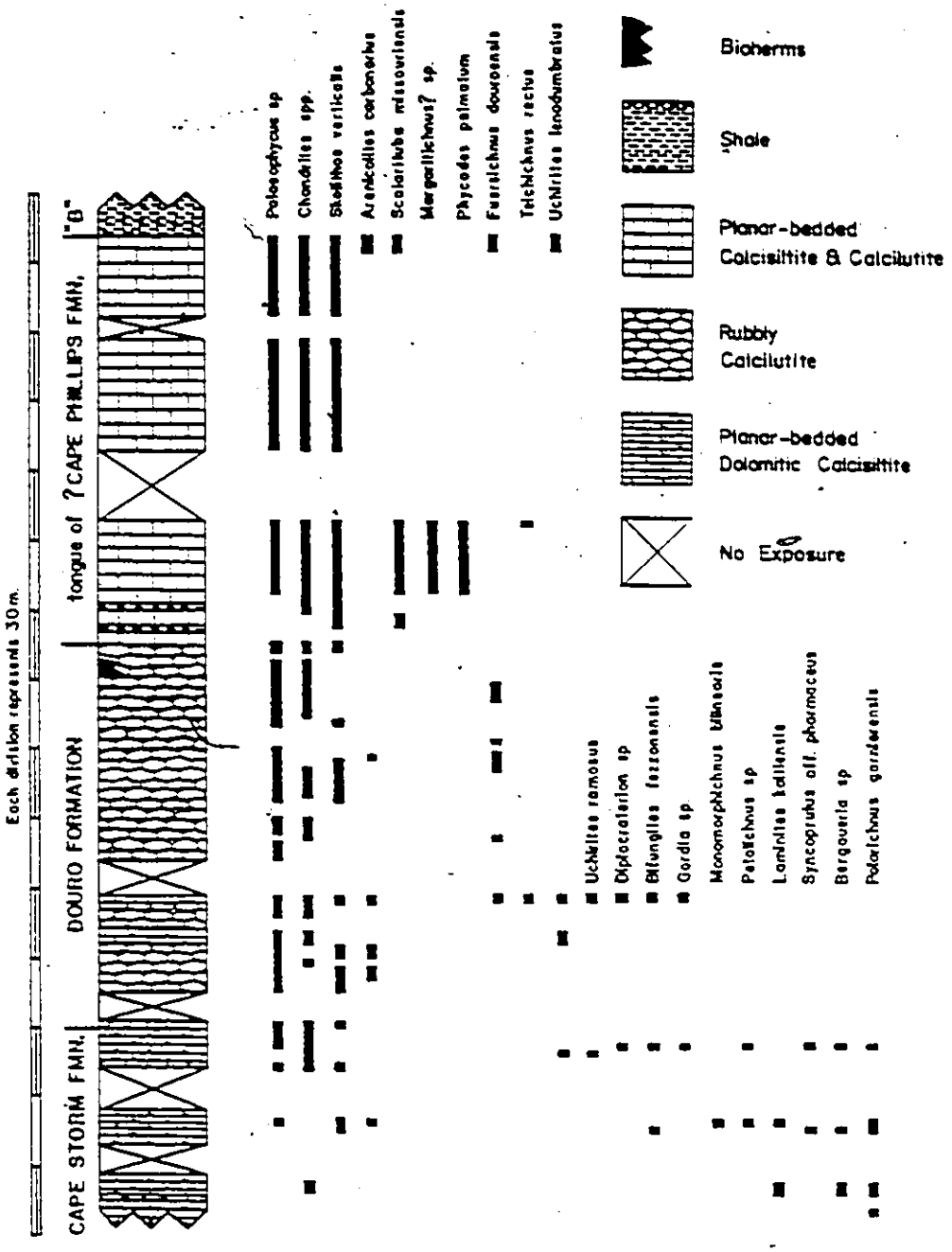
Trace fossil associations have been shown to be valuable paleoenvironmental indicators. Although they are not strictly depth controlled, ichnocoenoses are strongly influenced by a number of depth-related environmental variables including turbulence, degree of exposure, sediment character and food supply (Rhoads 1975; Seilacher 1978). Each of the environmental zones recognized in this study exhibits a distinctive association of trace fossils.

Intertidal Environments

Trace fossils were observed in approximately 25% of all units deposited under intertidal conditions. Trace fossils are considerably more common in strata deposited under low



Text-fig. 20. Stratigraphic distribution of trace fossils on southeastern Somerset Island. Data obtained from Two Rivers Bay (solid bars in basal 180 m of section), Fury Point (solid bars in upper 180 m of section) and other localities on Somerset Island (open bars). S.I. FMN = Somerset Island Formation.



Text-fig. (21. Stratigraphic distribution of trace fossils at Goodsir Creek, Cornwallis Island. "B" = member B of the Read Bay Formation (as defined by Thorsteinsson 1958).

intertidal conditions than in strata deposited in the high intertidal zone. This difference may have been due to different durations of subaerial exposure, most probably under arid conditions (Jones and Dixon 1975, p. 409).

The intertidal ichnocoenose is dominated by dwelling and feeding traces with fewer resting and crawling forms. Chondrites, Palaeophycus, Polarichnus, Bergaueria, Skolithos and Bifungites are common; Arenicolites, Laminites, Gordia, Petalichnus, Cochlichnus, Cruziana, Syncoprulus, Diplocraterion, Helicodromites, Monomorphichnus and Rusophycus are rare. This ichnocoenose is termed the "Polarichnus-Bergaueria association". It is analogous to the Skolithos ichnofacies (Seilacher 1967) which is a predominantly intertidal ichnocoenose dominated by dwelling traces.

Subtidal Shelf Environments

Rocks deposited under subtidal shelf conditions contain the greatest abundance and diversity of trace fossils. More than 60% of units contain trace fossils, chiefly feeding traces with fewer dwelling traces and relatively few crawling and resting traces. Palaeophycus, Chondrites, Skolithos, Fuersichnus, Arenicolites and Uchirites are common, Teichichnus, Bifungites, Cochlichnus, Gordia, Phycodes, Helicodromites,

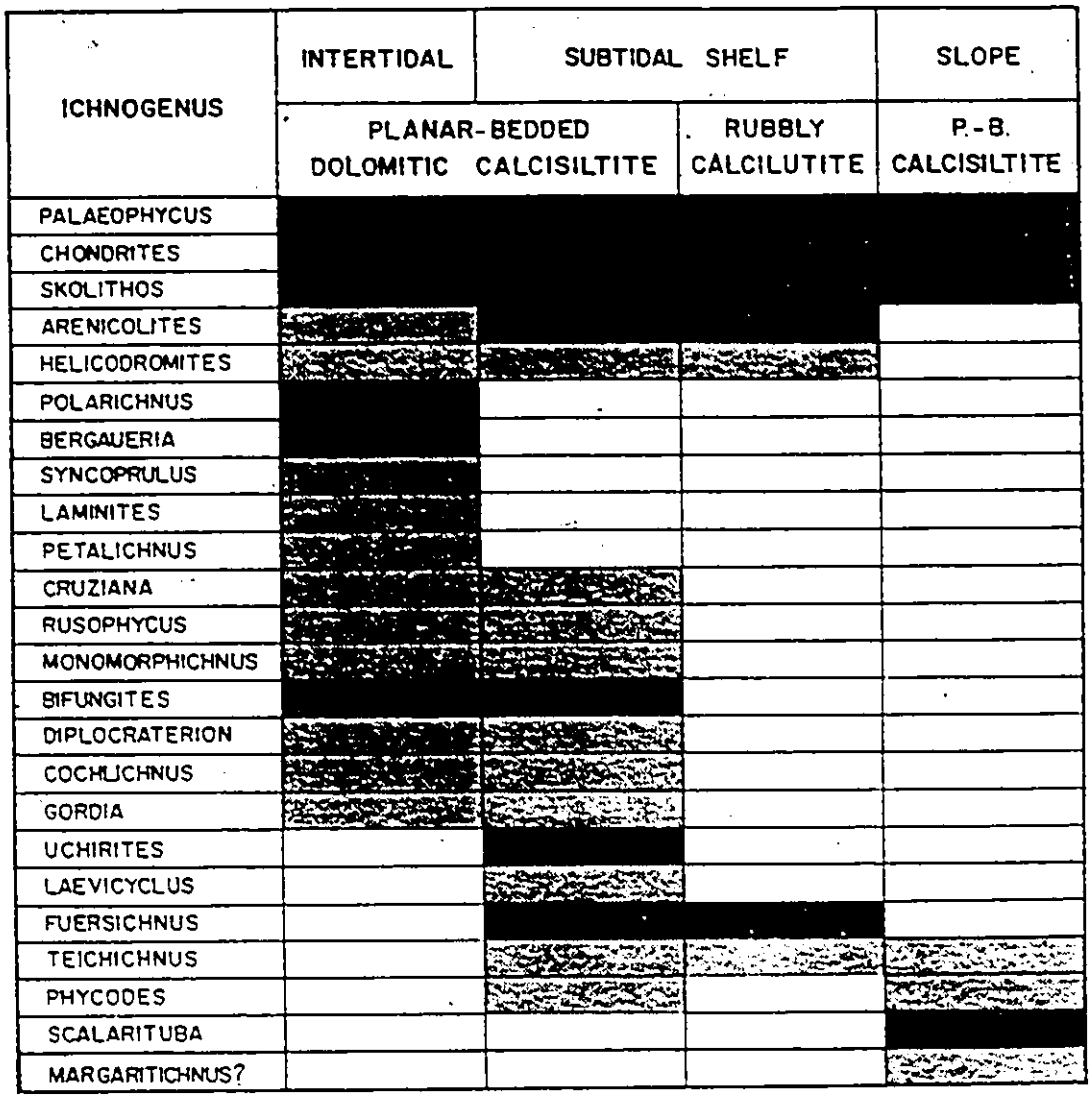
Diplocraterion, Monomorphichnus, Rusophycus, Cruziana and Laevicyclus are rare. This ichnocoenose is termed the "Fuersichnus - Uchirites association". It is analogous to the Cruziana ichnofacies (Seilacher 1964, 1967) which is a predominantly shallow subtidal ichnocoenose dominated by feeding traces, and arthropod resting and crawling traces.

Basin Slope Environments

Trace fossils are distributed sporadically in peri-platformal calcilutite and calcisiltite beds, but where ichnofossils occur they tend to be abundant. Skolithos, Chondrites, Palaeophycus and Scalarituba are common; Phycodes, Margaritichnus?, and Teichichnus are rare. This ichnocoenose is termed the "Scalarituba association". It is environmentally equivalent to the Zoophycos ichnofacies (Seilacher 1964, 1967); the apparent absence of this ichnogenus illustrates how unreliable single indicators can be in paleoenvironmental reconstruction.

Synthesis

Trace fossils are abundant in these Upper Silurian carbonates and occur in three associations, each restricted to a different sedimentary environment (Text-fig. 22). Associations are distinct; the only overlap is in the uppermost 10 m of the Douro Formation on Cornwallis Island where Fuersichnus,



Text-fig. 22. Lithologic and paleoenvironmental distribution of trace fossils in the study area. Blank area - not observed; light pattern - rare; dark pattern - common to abundant.

Uchirites and diminutive Scalarituba occur together. The overlap of the Fuersichnus-Uchirites and Scalarituba associations supports other paleontologic and sedimentologic evidence which suggests that these strata were deposited in a transitional environment with aspects of both deep subtidal shelf and basin slope conditions (Thomas and Narbonne 1979, p. 3).

Although each of the associations is similar in overall composition to one of Seilacher's (1964, 1967) marine ichnofacies, there are a number of differences in detail. Polarichnus and Bergaueria have proven reliable as bathymetric indicators in other studies (e.g. Crimes 1970b, p. 103; 1977, table 4; Narbonne et al. 1979), but ichnogenera such as Scalarituba, Uchirites and Laminites are eurybathic, and their apparent restriction to a single environmental zone in this study is only of local significance. Skolithos is equally abundant in all the environmental zones of this study, and trilobite traces diagnostic of the Cruziana ichnofacies occur in both intertidal and shallow subtidal deposits. Phycodes, generally regarded as a reliable indicator of the Cruziana ichnofacies, also occurs in basin slope deposits. These differences serve to emphasize the need to base paleoenvironmental reconstructions on the overall composition of the ichnocoenose, rather than on the occurrence of an individual "diagnostic" ichnofossil.

Studies by Rhoads (1967), Walker and Laporte (1970) and Fürsich (1975) have shown that intertidal deposits are commonly characterized by abundance of deep vertical burrows whereas subtidal deposits commonly contain mainly horizontal trace fossils. However, Frey (1970, pp. 32-33) believed that depth of burrowing is controlled by a wide variety of factors and is not a reliable bathymetric indicator. Both horizontal and vertical trace fossils are common in all the environmental zones of this study, and although the diversity of vertical burrows is slightly higher in intertidal deposits than in basin slope deposits, maximum depth (3 cm) and maximum density (150/100 cm^2) of vertical burrows is the same in both environmental zones. These observations support Frey (1970) in suggesting that depth of burrowing should be used with extreme caution as a bathymetric indicator.

SUBSTRATE CONSISTENCY

Substrate consistency is one of the most important factors controlling the distribution of benthic organisms (Rhoads 1970, pp. 401-404; Howard 1975, p. 141). Unlike other sediment characteristics such as composition and grain size, the original coherence of an ancient substrate cannot be observed directly. It is most commonly determined through examination of animal-sediment interrelationships.

The presence of numerous infaunal worm burrows in the rubbly calcilutites of the Douro Formation indicates that the substrate was relatively soft, although the absence of thick

burrow linings suggests that it was not thixotropic (cf. Frey 1970). Preservation of distinct burrow boundaries (cf. Rhoads 1970, pp. 399-400), fine arthropod scratch-marks (cf. Fürsich 1975, p. 156) and organism-induced microtectonics (cf. Osgood 1970, pp. 380-381) also suggest a relatively cohesive substrate. Palaeophycus, the most common trace fossil in the Douro Formation, exhibits circular burrow cross-sections and is commonly infilled with late diagenetic, void-filling spar (Pl. 14, figs. 7;8); these features indicate that the calcilutites have not been compacted to any significant degree, and could reflect either a firm substrate or early lithification of the sediments.

Burrows in calcisiltite beds of Cape Storm, Leopold and Douro Formations apparently lack sparite infillings and thick burrow linings. The presence of distinct burrow boundaries, circular burrow cross-sections, organism-induced microtectonics, and fine arthropod scratch marks in some units suggests a relatively cohesive substrate. In contrast, other units, particularly intertidal deposits, exhibit soft-sediment deformation structures (Dixon and Jones 1978, Pl. 1, Fig. 6), or contain burrows which exhibit indistinct outlines, lenticular cross-sections, collapse features and poor preservation of microtectonics, suggesting a thixotropic substrate. Substrates composed of silt-sized carbonates probably exhibited all gradations from firm to thixotropic.

The relatively simple tubiform burrows Palaeophycus and Planolites are common in most Phanerozoic sedimentary sequences. Although they are eurybathic and euryhaline, these ichnogenera can yield valuable information on substrate consistency through details of their nature of preservation (e.g. burrow cross-sectional shape, clarity of burrow outline, presence or absence of microtectonics, etc.). Moreover, their broad stratigraphic and environmental ranges would permit precise comparisons of substrate consistency of rocks of most ages and environments. In this way, these "non-diagnostic" trace fossils may eventually prove exceedingly useful in environmental reconstruction.

TRACE FOSSIL ASSEMBLAGES OF THE SUBTIDAL SHELF

Subtidal shelf deposits of the Douro Formation contain a diverse ichnocoenose, herein termed the Fuersichnus-Uchirites association. This association can be subdivided into three assemblages, each restricted to a different lithotype. Rubbly calcilutite contains a Fuersichnus assemblage consisting of numerous Palaeophycus, Chondrites, Fuersichnus, Skolithos and Arenicolites with fewer Teichichus and Helicodromites (Text-fig. 22). Planar-bedded calcisiltite contains a Uchirites assemblage which includes all forms present in the Fuersichnus assemblage (in about the same order of importance), together with numerous Uchirites and Bifungites and fewer

Cochlichnus, Gordia, Phycodes, Diplocraterion, Rusophycus, Monomorphichnus, Cruziana and Laevicyclus (Text-fig. 22). Calcirudite and coarse calcarenite only rarely contain identifiable trace fossils due to the coarse grain-size relative to the size of the trace fossils.

The Uchirites assemblage occurs mainly in shallow subtidal shelf deposits, whereas the Fuersichnus assemblage occurs in both shallow and deep subtidal shelf deposits. However, with the exception of Bifungites and Diplocraterion, all ichnofossils of the Uchirites assemblage have been previously reported from deeper water environments as well, and there is little reason to believe that they were unusually restricted in the study area. Furthermore, the Uchirites assemblage is not present in rubbly calcilutites deposited under shallow subtidal conditions, but is present in one planar-bedded unit at the top of the ?Cape Phillips Formation at Goodsir Creek (Text-fig. 21) which was deposited under conditions transitional between deep subtidal shelf and basin slope. These occurrences suggest that, within these subtidal shelf deposits, the primary control on the distribution of the Uchirites assemblage was lithologic rather than bathymetric.

Traces typical of the Uchirites assemblage occur in a wide variety of rock-types in other sequences, suggesting that the originators of this assemblage were not substrate controlled.

The calcisiltite beds exhibit many features typical of storm deposits (cf. Jones and Dixon 1976), but the Uchirites assemblage is relatively high in diversity whereas most ichnocoenoses of storm deposits are low diversity assemblages of dwelling traces.(Pemberton 1979, pp. 182-184).

Most trace fossils in this study were preserved through either toponomic or diagenetic processes. Toponomic processes comprise all methods whereby a trace produced in one type of sediment (typically mud) is cast by a different type of sediment (typically sand or silt) derived from the overlying or underlying bed. Toponomic processes were the predominant method of trace fossil preservation in siliciclastic sequences, but in this study were only important in calcisiltites. Diagenetic processes involved the selective diagenesis of either the trace fossil or, less commonly, the surrounding matrix. The most important diagenetic process in the carbonates of this study was the selective dolomitization of burrow fills, probably because their increased permeability favoured the flow of dolomitizing fluids (Jones et al. 1979). Burrows also commonly contain spar which exhibits fabrics typical of late diagenetic void-filling cement (cf. Bathurst 1971), indicative of selective cementation of an open burrow system. Rarely, burrows are partly or completely infilled with pyrite, probably because organic matter in the burrows led to the formation of a reducing micro-environment (cf. Kennedy 1975, p. 390,392). Most trace fossils in rubbly calcilutite were preserved through diagenetic processes.

The two major processes of preservation acted independently to produce markedly different assemblages. Selective diagenesis occurred most commonly in calcilutites, whereas toponomic processes were most important in calcisiltites. Toponomic processes preserved traces predominantly in semi-relief, in contrast with diagenetic processes which resulted exclusively in full reliefs. Both epifaunal and infaunal traces were preserved by toponomic processes, whereas only infaunal burrows were preserved through diagenetic processes. In addition, the quality of preservation is generally poorer among traces preserved through diagenetic processes, particularly those which were selectively dolomitized.

In view of the different modes of trace fossil preservation in the two lithotypes, it is most likely that the apparent lithologic association of these assemblages reflects preservational rather than environmental factors. Many of the trace fossils of the Uchirites assemblage were not readily preservable in rubbly calcilutite. Selective diagenesis in the calcilutites did not preserve epifaunal traces, most probably because they were later infilled with material identical to that of the overlying bed and hence did not act as conduits for diagenetic fluids. Pressure solution and the formation of nodules modified all original bedding surfaces in the calcilutites, destroying all bedding-plane traces. These two processes selectively

removed epifaunal traces (e.g. Rusophycus, Monomorphichnus, Cruziana) and traces only readily identifiable on bedding surfaces (e.g. Bifungites, Laevicyclus, Phycodes) from the calcilutite ichnocoenose. Selective dolomitization obliterated fine morphologic details (e.g. striae on Uchirites) resulting in later identification as non-diagnostic forms such as Palaeophycus. Non-preservation of these and other traces of the Uchirites assemblage in rubbly calcilutite probably resulted in the relatively low diversity of the Fuersichnus assemblage.

DISCUSSION

Most ichnologic studies of Lower Paleozoic strata have been based on siliciclastic sequences. The recognition of equivalents of the Skolithos and Cruziana ichnofacies in this study suggests that trace fossil concepts, such as Seilacher's "universal ichnofacies", can be applied equally well to carbonate sequences (cf. Osgood 1970; Frey and Howard 1970; Kennedy 1975). None of the genera of this study are restricted to carbonate rocks, and most of the previously described species have also been reported from siliciclastic rocks deposited under equivalent environmental conditions. The mineralogic composition of the substrate was probably of less importance than other environmental variables such as substrate consistency and water turbulence in controlling the distribution of the trace-making organisms.

Nevertheless, the greater susceptibility of carbonates to early and late diagenetic processes presents special ichnologic problems. The influence of synsedimentary lithification on burrowing and boring organisms, and the role of burrowing organisms in the diagenesis of carbonates has recently been summarized by Kennedy (1975) and Bromley (1975). However, it has not generally been recognized that late diagenetic processes in carbonates can significantly reduce the diversity of an ichnocoenose. Selective diagenesis does not act uniformly on all traces produced; it enhances infaunal burrows (typically dwelling and feeding traces) but commonly has little or no effect on epifaunal traces (typically resting and crawling traces). Selective dolomitization and neomorphism of trace fossils can further bias the ichnocoenose towards simple eurybathic forms by obliterating fine morphologic details. Even trace fossils preserved in semi-relief through toponomic processes can later be destroyed by the diagenetic alteration of bedding planes during pressure solution, diagenetic segregation and the formation of nodules.

Selective diagenesis of trace fossils and the diagenetic alteration of bedding planes were important processes in the formation of many fine grained limestones. As a consequence, these limestones can exhibit ichnocoenoses which differ in preservation or composition from those preserved in environmentally equivalent siliciclastic sequences. An extreme example

is the formation of mottled limestones through the selective dolomitization of burrow fills (Kendall 1977; Morrow 1978). Trace fossils are abundant in these rocks, although in most cases they are poorly preserved and relatively low in diversity.

Preservational factors can even influence the recognition of an ichnofacies. Lower Paleozoic shallow marine siliciclastic deposits are characterized by a Cruziana ichnofacies containing numerous trilobite trace fossils (Seilacher 1964, 1970). Clastic limestones commonly contain a similar ichnocoenose (Osgood 1970; Pickerill and Forbes 1979; this study). Although rubbly and burrow-mottled dolomitic limestones commonly contain trilobite body fossils, trilobite trace fossils are only rarely preserved. In these limestones, the Cruziana ichnofacies is best recognized by the presence of infaunal feeding traces such as Phycodes and Rhizocorallium.

SYSTEMATIC PALEONTOLOGY

Repository. All type and figured specimens are in the repository of the Geological Survey of Canada, Ottawa (GSC).

Material. Material is listed for all new species, and for all species represented by less than 20 specimens. Geographic and stratigraphic locations of holotypes of new species accompanying the systematic descriptions; locations of figured specimens are described in the figure captions.

ARENICOLITES Salter, 1857

Type species. Arenicola carbonaria Binney, 1852, p. 192, subsequent designation of Richter 1924, p. 137.

Diagnosis. Simple U-tube without spreite, perpendicular to bedding plane (Häntzschel 1975, p. W38).

Arenicolites carbonarius (Binney), 1852

Plate 11, figs. 3,5

Diagnosis. Relatively small Arenicolites; maximum depth and distance across the "U" approximately equal, and less than 3 cm.

Description. The U-shaped burrows are vertical to slightly oblique with a maximum deviation of 35° from the vertical. Tube diameter is 1.5-3 mm; the tube walls are smooth and unlined. The shafts are parallel to slightly divergent and the distance across the "U" is 17-20 mm. The maximum observed depth was 18 mm. Specimens rarely exhibit a single funnel-shaped aperture up to 15 mm in diameter and 5 mm deep.

Preservation. Toponomic - full relief
Diagenetic - full relief (selective cementation; rarely selective dolomitization).

Remarks. The specimens are similar to those illustrated by Binney (1852, Pl. 1, fig. 2) except that all of his specimens are perpendicular to stratification, and many exhibit two funnel-shaped apertures. Binney considered that A. carbonarius was similar to the J- to U-shaped burrow of the deposit-feeding polychaete Arenicola. This burrow has a single funnel which serves as a collecting pit for nutrient-rich sediments (Schäfer 1972, p. 301-302). Funnel-shaped apertures are, however, exceedingly rare in the specimens of A. carbonarius in this study, and those present do not resemble the Arenicola collecting pits. Although some species of Arenicolites may have been constructed by deposit feeders

(Frey and Chowns 1972, p. 29), A. carbonarius was most probably the dwelling burrow of a small filter-feeding organism. Simple U-shaped burrows in Recent sediments are constructed by a variety of organisms including amphipods, echiurids, enteropneusts, holothurians and polychaetes (Schäfer 1972, p. 299). Arenicolites is most common in the shallow marine Skolithos and Cruziana ichnofacies, but has also been reported from flysch sequences (Hakes 1976, p. 20; Crimes 1977, Table 1).

BERGAUERIA Prantl, 1945

Type species. Bergaueria perata Prantl, 1945, p. 52, by original designation.

Diagnosis. Broad, unlined vertical cylinders; U-shaped in cross-section (Fürsich 1974b, p. 2).

Bergaueria sp.

Plate 11, fig. 2

Description. The burrows are hemispherical, 11-32 mm (average 16 mm) in diameter and 8-23 mm (average 18 mm) in depth. They are unlined, with a smooth external surface. Specimens rarely

exhibit concentric markings about a central depression. Maximum observed densities were approximately 10/100 cm^2. Specimens are most commonly isolated; where they are numerous, short strings of 3-5 apparently randomly overlapping specimens occur very rarely.

Preservation. Toponomic - convex hyporelief, rarely concave epirelief.

Remarks. Among the described species of Bergaueria, B. radiata Alpert, 1973 is most similar in size to B. sp. The latter lacks the radial ridges diagnostic of B. radiata, but this may, however, be due to the relatively poor quality of preservation of the specimens in this study. Bergaueria represents the resting or dwelling trace of an actinian anemone (Häntzschel 1962; Arai and McGugan 1968; Alpert 1973; Fürsich 1974b), and is typical of shallow marine deposits (Seilacher 1964, table 1; Crimes 1970b; 1977, table 4).

BIFUNGITES Desio, 1940

Type species. Bifungites fezzanensis Desio, 1940, p. 78, by original designation.

Diagnosis. Dumb-bell or double arrowhead-shaped structures on bedding surfaces.

Bifungites fezzanensis Desio, 1940

Plate 11, figs. 8,9

Description. Burrows occur as dumb-bell shaped ridges 4.1-15.0 mm (average 8.6 mm) long on soles. They exhibit two bulbous terminations 2-5 mm (average 3 mm) in diameter connected by a smooth cylindrical bar 0.8-2.0 mm (average 1.2 mm) in diameter. Terminations are predominantly hemispherical, but specimens commonly exhibit one or more spherical, arrowhead-shaped or irregularly shaped terminations.

Preservation. Toponomic-convex hyporelief.

Remarks. Bifungites has been regarded as the base of a U-shaped spreiten-burrow (Osgood 1970, p. 324), the base of an inverted π-shaped burrow without spreite (Mélou and Plusquellec 1975; Gutschick and Lamborn 1975) or a truncated spreiten-burrow (Seilacher 1955, p. 383). Unfortunately all specimens in this study occurred in semi-relief on erosion surfaces (cf. Seilacher 1969, p. 122); consequently the nature of the U-plane section

could not be determined. The relationship between Bifungites and the morphologically similar burrow Arthraria Billings is uncertain as the holotype of Arthraria is lost, but Bergström (1976, p. 1630) examined topotypic material and suggested that Arthraria is a junior synonym of Diplocraterion Torell.

The shape of the terminations has commonly been used to distinguish B. fezzanensis (hemispherical terminations) from B. halli (spherical terminations). However the presence of terminations of different shapes on a single bedding surface (Pl. 11, fig. 8) or even within single specimens (Pl. 11, fig. 9) suggests that this criterion is unreliable as a species indicator. Species based on size criteria also overlap, and are of questionable validity (Pickerill and Forbes 1977, p. 90).

Bifungites probably represents the dwelling trace of a polychaete, and is common in tidal and shallow subtidal deposits (Pickerill and Forbes 1977).

CHONDRITES Sternberg, 1833

Type species. Fucoides targionii Brongniart, 1828, p. 56, subsequent designation of Andrews 1955, p. 130.

Diagnosis. Tunnel systems possessing a small number of master shafts open to the surface which ramify with depth to form a dendritic network. The individual branches may or may not cross over and interpenetrate (Osgood 1970, p. 328).

Chondrites - type 1

Plate 11, fig. 7

Description. Specimens consist of a cluster of subvertical burrows surrounded by short secondary galleries that project from the main shafts in a radioblique pattern and become more horizontal distally. Branching proceeds to the second order and is predominantly alternate; the angle of bifurcation ranges from 40° to 85°. Individual branches are straight to gently curved, and up to 30 mm long; complete systems are up to 55 mm across. Burrow diameter is 0.6-1.3 mm and does not change appreciably within a single system. Burrows only rarely interpenetrate.

Preservation. Diagenetic - full relief (selective dolomitization)
Toponomic - full relief

Chondrites - type 2

Plate 11, fig. 6

Description. Specimens consist of a fan-shaped cluster of horizontal, straight to gently curved, branching burrows. Branching proceeds to at least the fifth order and is predominantly random; the angle of bifurcation ranges from 20° to 85°. Individual branches are up to 75 mm long. Burrow diameter is 0.9-1.2 mm and does not change appreciably within a single system. Interpenetration of burrows was not observed.

Preservation. Diagenetic - full relief (selective dolomitization)
Toponomic - full relief.

Remarks. Chondrites was originally described as an alga, and was the last of the fucoids to be generally recognized as a trace fossil (see Osgood 1970, pp. 328-332). The existence of twenty generic synonyms and more than 130 described species represents a serious if not impossible problem of synonymy (Chamberlain 1971a, p. 234). The problem is compounded by the fact that most of the forms were described in botanic rather than ichnologic terms.

The two types of Chondrites are readily separable in the study area, but in some other areas they apparently intergrade (pers. comm., A. Rindsberg, 1980). Chondrites - type 1 is broadly similar to Chondrites sp. A Frey and Chowns, 1972; Chondrites - type 2 is broadly similar to Chondrites sp. B Frey and Chowns, 1972.

Simpson (1957) suggested that Chondrites represents the regular probings of a sediment-ingesting worm, possibly a sipunculid. He demonstrated that the burrows were originally open, although the precise mechanism whereby the very long, narrow burrows were infilled is still uncertain (Ferguson 1965; Osgood 1970, pp. 338-339). Chondrites is eurybathic (Seilacher 1964).

COCHLICHNUS Hitchcock, 1858

Type species. Cochlichnus anguineus Hitchcock, 1858 p. 161, by monotypy.

Diagnosis. Regularly meandering smooth trails, resembling sine curve (Häntzschel 1975, p. W52).

Cochlichnus sp.

Plate 12, fig. 7

Description. The sinuous traces are 3-6 mm wide and up to 85 mm long; wavelength is 15-25 mm and amplitude is 3-5 mm.

Preservation. Toponomic - concave epirelief, convex hyporelief.

Remarks. A review of the literature suggests that two distinct forms are presently encompassed under Cochlichnus. Seilacher (1964, text-fig. 6) figured specimens of Sinusites (referred to Cochlichnus by Häntzschel 1975, p. W52) which are preserved in full relief and exhibit short, upwardly directed probes; these probably represent infaunal feeding burrows. In contrast, Moussa (1970) described Recent Cochlichnus which were formed as

crawling trails at the sediment-water interface. The specimens observed in this study were preserved only in semi-relief, and were probably also surface trails. Baldwin (1974) demonstrated experimentally that desiccation cracks commonly follow surface trails. One slab exhibits numerous desiccation cracks which follow the Cochlichnus trails along the surface of the slab but do not extend upwards into the overlying bed, further suggesting that these Cochlichnus specimens were surface trails. Further work is needed on type material to determine whether this difference is of taxonomic significance.

Cochlichnus is a eurybathic ichnofossil (Crimes 1970b, p. 106), and was most likely constructed by an annelid or nematode (Seilacher 1963, p. 82).

CRUZIANA d'Orbigny, 1842

Type species. Cruziana rugosa d'Orbigny, 1842, p. 30, by subsequent designation of Bassler 1915, p. 292.

Diagnosis. Elongate, bilobate, band-like furrows covered by herringbone-shaped ridges (after Häntzschel 1975, p. W55).

Cruziana problematica (Schindewolf), 1921

Plate 11, fig. 4

Diagnosis. Small Cruziana, 1-11 mm in width, with transverse to sub-transverse striae (after Bromley and Asgaard 1979, p. 68)

Description. The bilobate, band-like structures are 1.5-5 mm (average 4 mm) wide and up to 30 mm long. Numerous transverse striae spaced 0.3-0.5 mm apart extend from the median furrow to just beyond the edges of the furrows. Most specimens are regular in form, but one exhibits three coffee bean-shaped expansions connected by a band-like furrow.

Preservation. Toponomic - convex hyporelief.

Remarks. This species has had a rather confused nomenclatural history. Schindewolf (1921) originally named it Ichnium problematicum, but later (1928) regarded it as the type species of Isopodichnus Bornemann, 1889. This dimorphic genus comprises both band-like and buckle-like forms; these forms were distinguished from the morphologically similar genera Cruziana d'Orbigny and Rusophycus Hall, respectively, chiefly by the smaller width of Isopodichnus. Isopodichnus was regarded as an indicator of fresh-water environments, whereas Cruziana and Rusophycus were believed to be restricted to marine environments (Seilacher 1970; Trewin 1976). However Bergström (1976, p. 1628) Pickerill and Forbes (1979, p. 2029), and Hofmann (1979, pp. 34-36) subsequently described occurrences of

Isopodichnus in marine strata, and Bromley and Asgaard (1972, 1979) described fresh water Cruziana from the Triassic of east Greenland. In a superbly illustrated article Bromley and Asgaard (1979) demonstrated that Isopodichnus overlaps in size and morphology with Cruziana and Rusophycus, and recommended that Isopodichnus be regarded as a subjective junior synonym of these two genera. This paper follows their suggestion in referring the band-like form of Isopodichnus problematicus to the genus Cruziana.

The specimens in this study were preserved in convex hyporelief and do not extend up into the overlying bed; they were probably formed at the sediment-water interface. Cruziana problematica probably represents the crawling trace (Seilacher 1955) or feeding trace (Glaessner 1957) of a small arthropod, most likely a phyllopod or trilobite (Häntzschel 1975). C. problematica is the only species of Cruziana which is known to have been formed in both lacustrine and shallow marine environments (Bromley and Asgaard 1979).

DIPLOCRATERION Torell, 1870

Type species. Diplocraterion parallelum Torell, 1870, p. 13, by subsequent designation of Richter 1926, p. 214.

Diagnosis. Vertical U-shaped spreiten-burrows; interpreted as dwelling burrows (after Fürsich 1974a, p. 958).

Diplocraterion sp.

Plate 12, fig. 8 .

Description. The U-shaped burrows are vertical to slightly inclined with a maximum deviation of 25° from the vertical. They exhibit either a protrusive spreite or a wall of dolomitized sediment between the arms of the burrow. The ichnofossils are 19-37 mm (average 24 mm) long; depth could not be determined as all specimens were incomplete. In plan view (transverse section) the trace fossil is commonly dumb-bell shaped, with two circular burrows 5-6 mm in diameter connected by a bar of spreite 2.5-4.5 (average 3.5 mm) wide.

Preservation. Toponomic - full relief, concave hyporelief
Diagenetic - full relief (selective dolomitization)

Remarks. The taxonomy of Diplocraterion has been recently reviewed by Fürsich (1974a), who recognized five distinct species. Unfortunately, the specimens in this study are not complete, and thus cannot be identified to species level. Diplocraterion is generally regarded as the dwelling burrow of a suspension-feeding worm or arthropod (Fürsich 1974a,b), and is common in high-energy marine environments (Crimes 1977, Table 1), particularly in the shallow marine Skolithos ichnofacies (Seilacher 1967; Fursich 1975).

FUERSICHNUS Bromley and Asgaard, 1979

Type species. Fuersichnus communis Bromley and Asgaard, 1979, p. 59, by original designation.

Diagnosis. Horizontal, retrusive burrow complexes composed of bow to J-shaped fills showing varying degrees of organization from an ear- or tongue-shaped spreite to isolated curved burrows (after Bromley and Asgaard 1979, p. 59).

Fuersichnus douroensis sp. nov.

Plate 12, figs. 1,2,4,5

Etymology. From the Douro Formation, in which this ichnofossil is abundant.

Material. Approximately 200 of the several thousand observed specimens were collected. The holotype (GSC 64033) was collected from strata 14.7-17.1 m above the base of the Douro Formation along the side of an unnamed creek 3 km south of Two Rivers Bay, Somerset Island (Text-fig. 19, locality D).

Diagnosis. Fuersichnus exhibiting a well-developed, predominantly horizontal spreite.

Description. In plan view, the ichnofossils are oval to crescentic structures 39-112 mm (average 85 mm) long and 11-61 mm (average 35 mm) wide. Although commonly occurring in profusion on bedding surfaces, the burrows are predominantly isolated. Fan-shaped or radial patterns are rare, and may be fortuitous as no central connecting burrow was observed. Specimens exhibit slightly to markedly curved ridges representing a truncated spreite; the final burrow is commonly preserved as a smooth-walled, cylindrical, curved to J-shaped tube 6-11 mm in diameter. In transverse section, most specimens appear as a single subhorizontal spreite; specimens less commonly exhibit two or three stacked subhorizontal spreiten, or a spreite oriented slightly to markedly oblique to stratification (locally subvertical).

Preservation. Diagenetic - full relief (selective dolomitization)
Toponomic - full relief, convex hyporelief.

Comparisons. Fuersichnus comprises a continuous series from well-developed horizontal spreiten-burrows to isolated curved burrows. F. douroensis is the most highly developed member of this continuum. In plan view, it resembles the most highly developed specimens of F. communis, but differs in being composed of true retrusive spreite rather than a spreite-like pattern of closely packed burrows. In addition, specimens of

F. douroensis are 2-3 times as long as specimens of F. communis. Very highly developed specimens of F. douroensis resemble Rhizocorallium Zenker, but exhibit a bow- to J-shaped tube rather than the U-shaped tube with parallel arms diagnostic of Rhizocorallium. Specimens which exhibit possible fan-shaped and radial patterns are reminiscent of Asterosoma von Otto, but Asterosoma is most commonly composed of concentric lamellae packed about and below a horizontal tube whereas F. douroensis is composed of retrusive spreite. In addition F. douroensis comprises both oval and crescentic specimens, unlike Asterosoma which exhibits exclusively oval lobes. The absence of minor lamellae in the spreite (cf. Simpson 1970) and the rare occurrence of subvertical spreiten serve to distinguish F. douroensis from Zoophycos.

Remarks. The formation of a regular pattern of horizontal spreite suggests that the originator of Fuersichnus douroensis systematically mined nutrient-rich layers of the sediment for food. Tubes are smooth-walled and cylindrical, suggesting a vermiform originator. Fuersichnus communis was described from Triassic lacustrine deposits (Bromley and Asgaard 1979, pp. 76-77), whereas F. douroensis occurs in shallow subtidal limestones of Silurian age.

GORDIA Emmons, 1844

Type species. Gordia marina Emmons, 1844, p. 24, by monotypy.

Diagnosis. Long, slender, smooth, loosely meandering traces with numerous level-crossings (after Książkiewicz 1977, p. 155).

Gordia sp.

Plate 12, fig. 9

Description. The smooth, horizontal burrows are strongly curved, commonly overcrossing. Burrow diameter is uniform, and ranges from 0.8 to 1.4 mm in different specimens. Maximum observed length was 125 mm.

Preservation. Toponomic - full relief, convex hyporelief.

Remarks. Gordia was regarded as the senior synonym of several similar genera by Häntzschel (1975, p. W64), but the range of variation of the different species of Gordia remains uncertain. Gordia probably represents the feeding trace of a vermiform organism, and has been reported from a variety of marine environments (Chamberlain 1977, p. 12).

HELICODROMITES Berger, 1957

Type species. Helicodromites mobilis Berger, 1957, p. 540, by monotypy.

Diagnosis. Smooth, straight to slightly sinuous helical burrows 1-10 mm in diameter; axis of helix parallel to stratification; individual coils not in contact.

Helicodromites mobilis Berger, 1957

Plate 12, fig. 3

Diagnosis. Unbranched Helicodromites with burrow diameter 1-3 mm; distance between coils much greater than burrow diameter.

Description. Two specimens of the unbranched, helically-coiled, smooth-walled burrows were collected. Helices are dextrally coiled, with axes straight and parallel to stratification; the distance between coils is 3-4 times burrow diameter. The smaller specimen has a burrow diameter of 1.5 mm and a coil diameter of 4 mm, and in the larger specimen the measurements are 3 mm and 8 mm respectively.

Preservation. Toponomic - convex hyporelief, full relief.

Helicodromites arctatus sp. nov.

Plate 12, fig. 6

Etymology. Latin 'arctatus', compressed; referring to the very tight coil of the helix.

Material. Five specimens from the Douro Formation of Somerset and Prince of Wales Islands and the Leopold Formation of Somerset Island. Holotype (GSC 64039) collected from strata 255-266 m above the base of the Douro Formation, from crags along the side of an unnamed gorge 6.5 km south of Savage Point, Prince of Wales Island (Text-fig. 19, locality K).

Diagnosis. Branched and unbranched *Helicodromites* with burrow diameter 4-10 mm; distance between coils less than or equal to burrow width.

Description. The burrows are helically-coiled, smooth-walled cylinders with a diameter of 4-7.5 mm and distance between coils of 50-100% of this value; coil diameter is 10-16 mm. The axes of the helices are straight to sinuous and are parallel to stratification; the helices are either sinistrally or dextrally coiled and the direction of coiling changes from the main burrow to the branches. Two specimens are branched.

Preservation. Toponomic - convex hyporelief, concave epirelief, full relief.

Comparisons. Helicodromites has a greater burrow diamater than either Helicorhaphe Ksiazkiewicz or Helicolithus Azpietia-Moros, and further differs from the former by the separation between the coils and from the latter by the absence of first-order regular meanders. In Helicolithus, the direction of coiling changes at each of the first order meanders (Seilacher 1977a, p. 306), similar to the change in the direction of coiling from the main burrow to the branches in Helicodromites arctatus.

Specimens of Helicodromites mobilis in this study are similar to the holotype in respect to burrow diameter and distance between coils, but have a smaller coil diameter and exhibit dextral rather than sinistral coiling. However, as the type species is represented by only a single specimen from a well core (Berger 1957), the range of variation of H. mobilis is unknown. Furthermore, the presence of both sinistral and dextral coiling in H. arctatus and in species of Helicolithus and Gyrolithes de Saporta suggests that direction of coiling may be unreliable as a species indicator.

H. arctatus differs from H. mobilis in three major respects. The distance between coils is less than or equal to burrow diameter in H. arctatus, whereas in H. mobilis it is much greater than burrow diameter. The burrow diameter of H.

arctatus is about three times greater than that of the genotype. In addition, H. arctatus commonly exhibits branching, a feature not noted in H. mobilis.

Remarks. Horizontal helical burrows similar in size to Helicodromites have been reported in Recent sediments from two environments. Hertweck and Reineck (1966, p. 434), Reineck et al. (1967, pp. 242-243) and Hertweck (1972, p. 135) reported horizontal helical tubes which form the bases of large, irregular, U-shaped burrows constructed by the capitellid polychaete Notomastus. The burrows were formed in upper and lower offshore sediments by both suspension and deposit feeders (Hertweck 1975, p. 486). Müller (1971) observed horizontal helical burrows in aeolian sand dunes, and suggested that these were also constructed by worms. The specimens of Helicodromites in this study exhibit complex branching patterns and apparently lack vertical segments, and hence were probably constructed by deposit feeding worms. Specimens were observed in strata deposited under intertidal and subtidal shelf conditions.

LAEVICYCLUS Quenstedt, 1879

Type species. Cyclozoon philippi Wurm, 1912, p. 127, subsequent designation of Alpert and Moore 1975, p. 229.

Diagnosis. Vertical, cylindrical burrow; with circular markings concentric with the burrow on upper bedding surface (after Alpert and Moore 1975, p. 229).

Laevicyclus sp.

Plate 13, fig. 5

Description. The single specimen appears in epirelief as a central circular depression 3 mm in diameter surrounded by several concentric circles. Radial grooves 1.5-3 mm in diameter are also locally visible, particularly towards the edges of the specimen. The total diameter of the ichnofossil is 152 mm. The central depression continues through the rock as a subvertical cylindrical burrow at least 23 mm deep.

Preservation. Toponomic - full relief.

Remarks. The specimen occurs in a 1 mm thick layer of calcareous shale deposited in a trough surrounded by interference ripplemarks. Sectioning suggests that the radial grooves are strictly a surface feature and do not continue down in the underlying calcarenite. The position of a horizontal tube cutting the ichnofossil is suggestive of possible relationship between the

two (see also Osgood 1970, pl. 71, fig. 3), but this is not supported by the fact that its diameter is 3-5 times that of the central vertical burrow. The specimen of Laevicyclus in this study is considerably larger than any previously reported, but is within the size range of Palaeoscia floweri Caster, 1942 which was later questionably referred to Laevicyclus by Alpert and Moore (1975).

Seilacher (1955, p. 389) compared Laevicyclus with the traces produced by the recent polychaete Scolecolepis squamata Söderström. This worm lives in a vertical cylindrical burrow and gleans food from the substrate by rotating its tentacles in a circular pattern along the sediment-water interface. Laevicyclus is most common in shallow marine sequences (Frey 1970, p. 34), but has been reported in flysch deposits as well (Chamberlain and Basan 1978, p. 56).

LAMINITES Ghent and Henderson, 1966

Type species. Laminites kaitiensis Ghent and Henderson, 1966, p. 158, by original designation.

Diagnosis. Horizontal, unbranched, subcylindrical burrows 2-15 cm in diameter, internally composed of transverse concave lamellae representing a back-fill structure.

Laminites kaitiensis Ghent and Henderson, 1966

Plate 13, fig. 1; ?fig. 2

Diagnosis. As for genus.

Description. The burrows are horizontal, unbranched, gently to markedly sinuous with numerous transverse concave lamellae 1-10 mm apart. The spacing of the lamellae is constant within any individual, and does not vary regularly with diameter. Burrow cross-section is lenticular, with diameters 20-52 mm (average 31 mm). Maximum observed length was 220 mm.

Preservation. Fecal stuffing - full relief.

Comparisons. Laminites is similar in some respects to Beaconites Vialov 1962 and Scolicia de Quatrefages 1849, and has been variously referred to these ichnogenera. The monotypic ichnogenus Beaconites, first described from a field photograph of a slab of the Devonian Beacon Sandstone of Antarctica, was diagnosed as "Cylindrical hollow tubes (or semicylindrical grooves), diameter up to 1.5 cm, straight or bent, with septae of the same thickness as the length of adjacent hollow portions of the tubes." (Vialov 1962, p. 728). Webby (1968) recognized

two genera of septate burrows in the Beacon Sandstone, and referred only the smaller form (4-6 mm in diameter) to Beaconites. Gevers et al. (1971) also recognized the two forms, and believed that their "narrow form" (4-15 mm in diameter) was very similar to the specimens of Beaconites antarcticus in Vialov's (1962, fig. 9) photograph. Although they hesitantly referred the "giant form" (27-103 mm in diameter) to B. antarcticus as well, Gevers et al. (1971, p. 85) stated that "...the giant forms are so strikingly different in 'septal' shape and structure that a nomenclatural distinction seems justified." Häntzschel (1975, p. W45, fig. 28, 1) further complicated the problem by describing and figuring the "giant form" of Gevers et al. (1971) as Beaconites, which he regarded as a possible senior synonym of Laminites. However this creates a nomenclatural problem, as Häntzschel's diagnosis of Beaconites excludes the holotype! The present author agrees with Häntzschel that the "giant form" is probably synonymous with Laminites, but would restrict Beaconites to the "narrow form" of Gevers et al. (1971). This definition corresponds most closely with Vialov's (1962) original diagnosis, and Webby's (1968) subsequent usage of the name "Beaconites".

Gregory (1969) recognized a complete transition between typical Laminites and forms with a medium longitudinal gap in the transverse lamellae, a feature typical of Scolicia de

Quatrefages. Laminites is an infaunal burrow (Ghent and Henderson 1966), and thus cannot be classified as a true synonym of Scolicia s.s. which represents a surface trail (Häntzschel 1975). Nevertheless, the features described by Gregory (1969) suggest that Laminites should be included in the "Scolicia group", which comprises several ichnogenera of highly variable burrows and trails generally attributed to gastropods (Häntzschel 1962, p. 215).

Remarks. Laminites represents the feeding burrow of a holothurian (Ghent and Henderson 1966), annelid or gastropod (Gregory 1969), or echinoid (Ward and Lewis 1975). Laminites is eurybathic, occurring in marginal marine (Webby 1968; Gevers et al. 1971) and flysch sequences (Ghent and Henderson 1966; Gregory 1969).

MARGARITICHNUS Bandel, 1973

nom. subst. pro Cylindrichnus Bandel, 1967, p. 6, non-Cylindrichnus Toots in Howard 1966, p. 45.

Type species. Cylindrichnus reptilis Bandel, 1967, p. 6, by original designation.

Diagnosis. Ball-like structures 15-30 mm in diameter; originally spherical; commonly arranged like string of pearls; rarely connected by ridges which show crescentic transverse grooves (after Häntzschel 1975, p. W82).

Margaritichnus? sp.

Plate 13, fig. 4

Description. Each specimen consists of a sinuous, uniserial string of hemispherical bodies, each sphere in contact with the preceding and following one. Two specimens were collected: one consists of six hemispheres 23 mm in diameter; the other consists of thirteen hemispheres 12-14 mm in diameter. Sectioning one hemisphere did not reveal any internal structure.

Preservation. Toponomic - convex hyporelief.

Remarks. Due to their preservation in convex hyporelief, it is impossible to determine whether the individual bodies were originally hemispherical or spherical. For this reason, they are only questionably referred to Margaritichnus, as this genus is restricted to "originally spherical" bodies (Bandel 1967, p. 6; Häntzschel 1975, p. W82).

Bandel regarded Margaritichnus as a string of spherical fecal pellets. Hakes (1976, p. 30) observed evidence of vertical movement and local impingement of spheres in topotypic material, and concluded that Margaritichnus was formed "...by chance settlings of anemone-like organisms next to each other or in successive positions in the sediment". However Hakes' explanation does not readily account for the uniserial tangential contact of up to 13 spheres, the local connection of spheres by ridges exhibiting crescentic transverse grooves, or the common uniformity of size of spheres in a string. Furthermore, although several genera of hemispherical to cylindrical anemone burrows are known (e.g. Bergaueria, Kulindrichnus), it is difficult to imagine how an anemone could construct a truly spherical resting burrow. It is more likely that Margaritichnus represents a series of spherical excavations produced by an infaunal feeding or grazing organism.

MONOMORPHICHNUS Crimes, 1970a

Type species. Monomorphichnus bilinearis Crimes, 1970a, p. 57, by monotypy.

Diagnosis. A series of straight or slightly sigmoidal ridges sometimes repeated laterally; inferred to have been produced by a number of clawed limbs (after Crimes 1970a, p. 57).

Monomorphichnus bilinearis Crimes, 1970a, p. 57

Plate 15, fig. 12

Diagnosis. *Monomorphichnus* in which the ridges are grouped in pairs (after Crimes 1970a).

Description. Four specimens were collected. Each consists of 5-9 pairs of parallel straight ridges 12-30 mm long; the ridges in each pair are approximately equally developed. Associated tool marks indicate that the ridges were formed at angles 10-70° from the paleocurrent direction.

Preservation. Toponomic - convex hyporelief.

Remarks. Crimes (1970a) regarded *Monomorphichnus* as the trace of a swimming trilobite which periodically raked the sediment with its endopodite claws. *Monomorphichnus* resembles a number of inorganic sedimentary structures, principally brush marks and graptolite drag marks. Although no single feature is conclusive, common orientation at an angle to paleocurrent indicators, local occurrence in units lacking current indicators, association with confirmed trilobite trace fossils (*Rusophycus* and *Petalichnus*) and consistent occurrence of bifid ridges are considered to be evidence for an organic origin of the specimens in this study.

The specimens in this study were probably produced by a medium-sized trilobite with nine or more body segments and with two claws at the end of each leg. Trilobite traces are typical of the shallow subtidal Cruziana ichnofacies (Seilacher 1964).

PALAEOPHYCUS Hall, 1847

Type species. Palaeophycus tubulare Hall, 1847, p. 7, subsequent designation of Bassler, 1915, p. 939.

Diagnosis. Unbranched to irregularly branched, straight to slightly curved, horizontal to slightly inclined burrows 3-20 mm in diameter; interpreted as originally open burrow systems.

Palaeophycus sp.

Plate 14, figs. 1,2,5,7,8

Description. The smooth, horizontal, cylindrical burrows are 4-9 mm (average 5.5 mm) in diameter and up to 300 mm in length. Most specimens are irregularly branched. Burrow fill is structureless, and can be either similar or dissimilar to the host lithology.

Preservation. Toponomic - full relief, convex hyporelief

Diagenetic - full relief (selective dolomitization, selective cementation).

Remarks. The distinction between the morphologically simple burrows Palaeophycus and Planolites Nicholson, 1873 has been a matter of some controversy. In a recent review, Alpert (1975) suggested that Planolites and Palaeophycus be distinguished by the presence of true branching in the latter. However, this is problematic, as extreme crowding can make it difficult to determine whether true branching is present and short sections of branched burrows commonly appear unbranched. Moreover, Alpert's distinction is not based on characters evident in the type specimens; in fact, several of Hall's syntypes of Palaeophycus tubulare do not exhibit branching.

Osgood (1970, pp. 375-376) also reviewed this problem and noted that Planolites was originally restricted to actively-filled burrows whereas the type specimens of Palaeophycus show evidence of passive fill. He suggested that the two genera could be distinguished through a comparison of the lithologies of the burrow fill and host rock: Planolites exhibits a marked difference whereas Palaeophycus does not. However this distinction is not always practical (Hakes 1976, p. 32). In the present study,

burrow fill commonly varied from calcilutite or calcisiltite (similar to the host rock) to sparite (dissimilar to host rock) along the length of a single burrow, and there are numerous examples of a geopetal calcilutite/sparite fill (Pl. 14, fig. 7). Strict application of Osgood's diagnosis in these cases would necessitate a change in nomenclature along the length of the burrow, or even from bottom to top. Selective dolomitization of burrow fills further restricts the usefulness of this distinction. However the original intent of Osgood's distinction, active versus passive fill, reflects a major ethologic distinction which is probably of generic significance.

The presence of void-filling spar in many of the burrows (Pl. 14, figs. 7,8) indicates that they were originally open burrow systems. Burrows filled predominantly with calcilutite or calcisiltite commonly exhibit a thin channel of sparite at the top of the burrow (Pl. 14, figs. 2,5); Seilacher (1968, p. 200) suggested that similar structures in Thalassinoides Ehrenberg represent fill channels on the crests of passively infilled open burrow systems. Specimens of Palaeophycus are commonly surrounded by micro-tectonic fractures (Pl. 14, figs. 7,8), suggesting that they were constructed by forcible penetration of sediment.

Fucusopsis Palibin occurs as hemicylindrical, unbranched to irregularly branched sole ridges covered with discontinuous longitudinal striae. Osgood (1970, pp. 300-381) regarded Fucusopsis sulcatum (Miller and Dyer) as a Palaeophycus-like burrow constructed just above an interface, the forcible penetration of sediment causing longitudinal tensional microfaults in the basal laminae of the bed. The present study supports this hypothesis. In one specimen (Pl. 14, fig. 1) part of the microfaulted silt layer has flaked off, revealing a Palaeophycus burrow beneath; in another example, a specimen of Fucusopsis sulcatum passes laterally into a branched Palaeophycus. These occurrences suggest that Fucusopsis sulcatum is a preservational variant of Palaeophycus and should not be regarded as a distinct species.

More than 50 species of Palaeophycus have been named, most of them based on relatively minor differences in morphology or preservation. Monographic study of this genus is necessary before meaningful specific names can be applied.

A number of authors (e.g. Osgood 1970, p. 376) have compared Palaeophycus to the burrow of Glycera. This predaceous polychaete constructs a two-part burrow, with a central tube

that serves as permanent dwelling and a number of temporary foraging offshoots (Frey and Howard 1972, p. 179); burrows are constructed by forcible penetration of sediment (Ockelmann and Vahl 1970). However the burrows of Glycera are predominantly oblique, whereas most Paleozoic specimens of Palaeophycus are strictly horizontal. In view of its simplicity, broad environmental tolerance, and long time range, it is probable that Palaeophycus could have been constructed by a wide variety of organisms (Osgood 1970). Palaeophycus represents a dwelling (Frey and Chowns 1972, p. 32) or crawling (Osgood 1970) trace.

PETALICHNUS Miller, 1880

Type species. Petalichnus multipartitus Miller, 1880, p. 222, by monotypy.

Diagnosis. Trail, 1-3 cm wide, consisting of two parallel series of single or bifid imprints. Imprints elongate obliquely to trail axis; 9-12 imprints per set (after Osgood

1970, p. 362 and Häntzshel 1975, p. W91).

Petalichnus sp.

Plate 14, fig. 9

Description. Seven specimens were collected. The trails are 15-24 mm wide (average 18 mm) and consist of two parallel series of bifid imprints elongate at an angle of 55-85 degrees from the trail axis. Due to the discontinuous nature of the trails, it was not possible to determine the number of imprints per set.

Preservation. Toponomic - convex hyporelief.

Remarks. Following Seilacher (1955, pp. 342-343) most authors have referred these relatively simple trails to Diplichnites Dawson, 1873. However Osgood (1970, p. 352) and Briggs et al. (1979, pp. 288-289) noted that Diplichnites differs from these trails in size, environment and presumed originator, and suggested that Diplichnites be restricted to Dawson's original usage.

Petalichnus was probably produced by a medium-sized trilobite walking straight ahead (Osgood 1970, p. 355); the direction of movement is inferred to have been opposite to the direction of convergence of the pairs of imprints (Seilacher 1955, pp. 342-346). The bifid imprints suggest that the trilobite had two claws on each foot. Trilobite tracks are typical of the shallow marine Cruziana ichnofacies (Seilacher 1964).

PHYCODES Richter, 1850

Type species. Phycodes circinnatus Richter, 1853, p. 20, by subsequent monotypy (see Magdefrau 1934, p. 260).

Diagnosis. Bundled structures of flabellate or broom-like pattern, consisting of horizontal tunnels; proximal part of main tunnels unbranched, distal tunnels divide at acute angles into several free cylindrical tunnels; main branches may show structure similar to retrusive spreiten (after Häntzschel 1975, p. W93).

Phycodes palmatum (Hall), 1852)

Plate 13, figs. 3,6

Diagnosis. Phycodes exhibiting few branches arranged in a palmate pattern.

Description. Specimens exhibit four or five cylindrical tubes which branch from a main shaft in a palmate pattern, then pass upwards into the overlying bed. The main shaft is 5-8 mm in diameter, and the secondary branches are 4-6 mm in diameter. The main burrow and proximal parts of the secondary branches exhibit retrusive spreite.

Preservation. Toponomic - full relief, convex hyporelief.

Remarks. The figured specimens closely resemble Hall's (1852) three syntypes of Buthotrephis palmata, subsequently referred to Phycodes by Seilacher (1955, p. 383). Phycodes represents the feeding trace of a vermiform organism (Seilacher 1955; Häntzschel 1975). Phycodes has been previously reported only from the shallow marine Cruziana ichnofacies (Seilacher 1964), although Gregory (1969) described a possible occurrence from a Miocene flysch.

POLARICHNUS Narbonne in Narbonne et al., 1979

Type species. Polarichnus garnierensis Narbonne in Narbonne et al., 1979, p. 133, by monotypy.

Diagnosis. Vertical, U-shaped burrow 1-15 cm in length, burrow cross-section subrectangular to elliptical. Appearing in epirelief as a raised rectangular zone of disturbed sediment exhibiting numerous gently curved transverse ridges concave towards the centre of the structure (after Narbonne et al. 1979, pp. 133-134).

Polarichnus garnierensis Narbonne in Narbonne et al., 1979

Plate 14, fig. 3

Diagnosis. As for genus.

Description and Remarks. Polarichnus was discussed in detail by Narbonne et al. (1979) who based their study largely on material from the Cape Storm and Leopold Formations of Somerset and Cornwallis Islands. This description will not be repeated here, but one correction is necessary. Narbonne et al. (1979) interpreted the concave ridges as microtectonic features, formed during the construction of a dwelling trace by forcible penetration of sediment. However, some specimens subsequently collected illustrate that, instead, the ridges are the edges of spreiten exhibiting both major and minor lamellae; this would

suggest that Polarichnus represents a feeding trace. Polarichnus has, thus far, been reported only from Siluro-Devonian boundary strata deposited in tidal flat environments (Narbonne et al, 1979).

RUSOPHYCUS Hall, 1852

Type species. Fucoides biloba Vanuxem, 1842, p. 72, by original designation of Hall 1852, p. 23.

Diagnosis. Short bilobate buckle-like forms, resembling shape of coffee beans; lobes transversely wrinkled by anterolaterally directed coarse or fine striae; with deep median furrow; outline mostly elliptical (Häntzschel 1975, p. W101).

Rusophycus pudicum Hall, 1852

Plate 15, fig. 11

Diagnosis. Fairly deep Rusophycus with irregular transverse scratches and commonly with impressions of pleural spines and genal angles (Seilacher 1970, p. 471).

Description. Traces are bilobate with forwardly expanding lobes and a moderately developed median furrow. Transverse striae are poorly developed. Three specimens were collected: the Douro specimens are 35 mm long and 15-19 mm wide; the Leopold specimen is 12 mm long and 8 mm wide.

Preservation. Toponomic - convex hyporelief, concave epirelief.

Remarks. The nomenclatural status of Rusophycus and its relationship to Cruziana d'Orbigny are subjects of considerable controversy. This paper follows Osgood (1970), Crimes (1975), Häntzschel (1975) and Bergström (1976) in retaining Rusophycus as a distinct genus. Although some specimens may have been feeding or dwelling traces, most were probably trilobite resting traces (Seilacher 1970). Osgood's (1970, Pl. 58, figs. 4,5) figures of an Ordovician specimen of R. pudicum with its producer, Flexicalymene meeki Foerste, preserved in place, have led most workers to suggest a calymenid originator for R. pudicum. Calymenids, however, have not been reported from the Douro Formation on Somerset Island, although encrinurids similar in size and shape to R. pudicum are common. Rusophycus is typical of the shallow marine Cruziana ichnofacies (Seilacher 1964).

SCALARITUBA Weller, 1899

Type species. Scalarituba missouriensis Weller, 1899, p. 12, by monotypy.

Diagnosis. Predominantly horizontal, subcylindrical, sinuous to meandering burrows with fine, transverse curved scalariform ridges; commonly exhibiting lateral, hemispherical, bioturbated lobes.

Scalarituba missouriensis Weller, 1899, p. 12

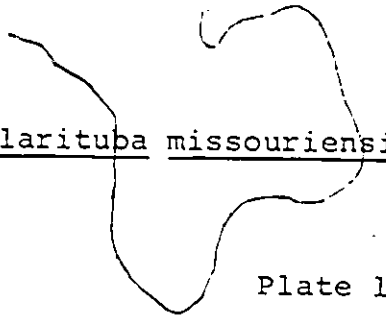


Plate 15, fig. 6

Diagnosis. As for genus.

Description. The horizontal, highly sinuous tubes exhibit elliptical cross-sections. Where preserved in hyporelief, the tubes are flanked by lobes of bioturbated sediment arranged in an opposite pattern. Burrow diameter is 2-12 mm, and the diameter of the tubes is 1-5 mm.

Preservation. Fecal tube: Diagenetic - full relief (selective dolomitization)

Lateral lobes: Toponomic - convex hyporelief.

Remarks. Seilacher and Meischner (1965, p. 615) pointed out similarities between Scalarituba Weller (fecal tube with transverse scalariform ridges commonly surrounded by a bioturbate halo), Nereites Macleay (fecal tube with transverse scalariform ridges with lateral bioturbate lobes) and Neonereites Seilacher (bioturbate lobes without a central fecal tube), which they regarded as preservational variants. Chamberlain (1971a, pp. 228-229) regarded Neonereites as a junior synonym of Scalarituba, and restricted Nereites to forms in which subsequent meanders were in contact with each other. In contrast, Häntzschel (1975) and Hakes (1976) preferred to retain Scalarituba and Neonereites as separate genera. In the present study, fecal tubes were preserved through selective dolomitization and thus occur both within beds and at interfaces, whereas the lateral lobes are preserved through toponomic processes and thus occur only at interfaces. It would be inconsistent to identify specimens within a bed as Scalarituba, while simultaneously regarding the specimens on its sole as Neonereites. Chamberlain's (1971a) suggestion that Neonereites is a junior synonym of Scalarituba is therefore adopted in this paper.

The mode of formation of Scalarituba was discussed in detail by Chamberlain (1971a). Scalarituba represents the feeding or grazing trace of a vermiform organism (Chamberlain 1971a; Hakes 1976). Specimens in the present study are highly

sinuous and do not cross-over, and hence are probably grazing traces (pascichnia). Selective dolomitization of the fecal tube has obliterated most of the scalariform ridges; as a result the specimens resemble the "fecal ribbon form of Scalarituba" described by Chamberlain and Clark (1973, p. 678).

Scalarituba is eurybathic (Seilacher 1964), but is especially common in offshore and slope deposits (e.g. Chamberlain 1971b). Specimens in the basin slope deposits overlying the Douro Formation on Cornwallis Island average 10 mm in width, with the fecal tube 4-5 mm in width. The uppermost 10 m of this succession represents a transition into subtidal shelf deposits; Scalarituba is less common in these strata, and is represented by specimens 2-4 mm wide with a fecal tube 1 mm in diameter. This supports the suggestion by Martintsch and Finks (1978), that specimens of Scalarituba formed under unfavourable environmental conditions tend to be smaller than those formed in an optimum environment.

SKOLITHOS Haldeman, 1840

Type species. Fucoides? linearis Haldeman, 1840, p. 3, by monotypy.

Diagnosis. Single, unbranched, vertical to gently inclined, cylindrical to subcylindrical burrow; 1-15 mm in diameter.

Skolithos verticalis (Hall), 1843

Plate 15, fig. 5

Diagnosis. Burrows cylindrical to prismatic (where in contact), straight to curved, vertical to inclined. Diameter 1 to 4 mm, length 2 to 15 cm. Burrow wall smooth, rarely corrugated (Alpert 1974, p. 664).

Description. The burrows are straight to slightly curved unbranched cylinders oriented 0-30° from vertical. Burrow diameter is 2-4 mm and the maximum observed depth was 30 mm. The walls are smooth and most are unlined; pyritic films on the walls of several burrows may represent diagenetic alterations of original mucus linings. Burrows are most commonly isolated, but densities of approximately 150/100 cm^2 occur rarely in strata deposited under intertidal, subtidal shelf and basin slope conditions.

Preservation. Toponomic - full relief
Diagenetic - full relief (selective cementation; rarely selective dolomitization and selective pyritization).

Remarks. The taxonomy of Skolithos has recently been reviewed by Alpert (1974) who recognized five distinct species and later (1975) proposed a sixth. Skolithos probably represents the dwelling burrows of filter feeders, possibly annelids (Richter 1921) or phoronids (Fenton and Fenton 1934).

Seilacher (1967) established the Skolithos facies as the shallowest marine ichnofacies in his bathymetric zonation. Although isolated specimens of Skolithos have been reported from neritic, bathyal and even abyssal environments (e.g. Crimes 1977, Table 4; Ekdale and Berger 1978), occurrences of deeply dug, closely crowded specimens ("pipe-rock") have thus far only been reported from nearshore environments.

SYNCOPRULUS Richter and Richter, 1939a

Type species. Syncoprulus pharmaceus Richter and Richter, 1939a, p. 164, by monotypy.

Diagnosis. Simple, unbranched or branched, tubular burrows filled with fecal pellets.

Syncoprulus aff. pharmaceus Richter and Richter, 1939a

Plate 11, fig. 1

Description. Nine specimens were collected. The horizontal, sinuous burrows rarely exhibit branching. Burrows are elliptical in transverse section, and range from 9-16 (average 11.5) mm in diameter; the maximum observed length was 170 mm. Burrows are filled with subspherical to elliptical pellets 2-3 mm long and 1-2 mm wide.

Preservation. Fecal packing - full relief.

Remarks. Despite several recent attempts at clarification, the taxonomy of pellet-filled burrows remains confused. One major question is whether the pellets and burrows should be named separately or grouped under the same name. Article 24b(i) of the International Code of Zoological Nomenclature states: "The Law of Priority applies when any part of an animal is named before the whole animal". This regulation is clearly applicable where a name is applied to a trilobite pygidium before a whole specimen is discovered, but is of questionable applicability in the case of fecal pellets and pellet-filled burrows. The same type of pellet commonly occurs both as isolated individuals and in a variety of burrow-types (e.g. elliptical pellets occur in Syncoprulus, Quebecichnus, and some species of Chondrites and Granularia), and different types of pellets commonly occur in otherwise

similar burrow-types. Moreover, pellets can filter into open burrows (Simpson 1957), where they may be mistaken for the pellets of the burrowing organism. For these reasons, it is probably best to regard coprolites as separate from trace fossils (cf. Häntzschel 1975, p. W139).

Simple pellet-filled burrows have been referred to Alcyonidiopsis Massalongo, 1856 and Syncoprulus Richter and Richter, 1939a by various authors. Alcyonidiopsis is the earliest named pellet-filled burrow (Chamberlain 1977, p. 7). However this name apparently was not used during the sixty-three years preceding 1955, and hence should be considered a nomen oblitum (International Code of Zoological Nomenclature, Article 23b). It is therefore unavailable; and is not to be used unless the International Commission on Zoological Nomenclature so directs. Tomaculum Groom is a commonly cited name which was first applied to strings of cylindroidal to elliptical pellets of unknown origin. Groom's (1902, p. 127-128) original description is somewhat vague, but it is probable that he intended the name to refer to the individual pellets rather than the burrows (Hofmann 1972, p. 194). Richter and Richter (1939a) also described burrows filled with cylindroidal to elliptical fecal pellets, naming the pellets Coprulus and the burrows Syncoprulus. They later (1939b) regarded Syncoprulus as a subjective junior synonym of Tomaculum, but Hofmann (1972)

has pointed out that Coprulus, rather than Syncoprulus, should have been rejected as the synonym.

From the foregoing discussion, it would appear that Syncoprulus Richter and Richter, 1939a is probably the oldest available name for simple, pellet-filled burrows. The specimens in this study are similar in size to the genotype, S. pharmaceus, but differ in the presence of rare branches. The pellets are slightly less elliptical than those commonly referred to Tomaculum.

Syncoprulus probably represents the feeding trace of a polychaete (Chamberlain 1977).

TEICHICHNUS Seilacher, 1955

Type species. Teichichnus rectus Seilacher, 1955, p. 378, by monotypy.

Diagnosis. Long, wall-like spreite-burrow, formed by vertical displacement of horizontal or oblique tubes (after Fürsich 1974b, p. 40).

Teichichnus rectus Seilacher, 1955

Plate 14, figs. 4,6

Diagnosis. Simple, straight or sinuous Teichichnus (Fürsich 1974b, p. 40).

Description. Two distinct size groupings are present. The smaller one comprises straight to slightly sinuous burrows 3-6 mm (average 4 mm) wide, up to 55 mm long and up to 14 mm high. The larger form comprises straight to irregularly sinuous burrows 9-15 mm (average 12.5 mm) wide and up to 400 mm long and 25 mm high. Both forms exhibit a retrusive or protrusive spreite, or a wall of dolomitized sediment; the septa are parallel to stratification.

Preservation. Toponomic - full relief
Diagenetic - full relief (selective dolomitization)

Remarks. Teichichnus was probably produced by an organism systematically mining the sediment for food by the vertical displacement of a subhorizontal burrow. Teichichnus occurs throughout a broad range of environments (Chamberlain 1978b, fig. 131).

UCHIRITES Macostay, 1967

Type species. Uchirites triangularis Macostay, 1967, p. 38, by monotypy.

Diagnosis (emend.). Unbranched or branched burrows 1-15 mm in diameter; covered with numerous fine striae crossing exterior surface obliquely and converging near lower and upper crests of burrows; occurring on bedding surfaces as ridges with triangular, subtriangular or bilobate transverse sections.

Uchirites lenadumbratus (Chamberlain), 1971a

Plate 12, fig. 10; Plate 15, fig. 2

1970 Gyrochorte ichnosp. a; Książkiewicz, p. 288; pl. 1, figs. a1, a2.

v1970 Cruziana?; Rodriguez and Gutschick, pl. 9, fig. d; pl. 10, fig. b.

v*1971a Sustergichnus lenadumbratus Chamberlain, p. 231; pl. 31, figs. 8,11.

1971b Sustergichnus; Chamberlain, text-fig. 6, 35

1975 Sustergichnus lenadumbratus Chamberlain; Häntzschel, p. W112; figs. 68a,b.

v1977 Cruziana?; Gutschick and Rodriguez, text-fig. 3a; pl. 1, fig. h.

1977 Gyrochorte burtani Książkiewicz, pp. 113-114; pl. 11, figs. 1-5; text-fig. 19.

1978a Sustergichnus; Chamberlain, text-figs. 2.20, 4.25.

1978 Sustergichnus; Chamberlain and Basan, text-figs. 7,8,10,11

Diagnosis. Unbranched Uchirites occurring on bedding surfaces as ridges triangular to bilobate in transverse section; with smooth-walled inner core circular to almond-shaped in transverse section.

Description. The unbranched, straight to gently curved burrows occur as hypichnial ridges 1.5-8 (average 5.8) mm wide and up to 110 mm long. Ridges are triangular to bilobate in transverse section; ridge crests most commonly point downwards, but are rarely oriented up to 90° from the vertical. Burrows exhibit numerous fine striae which cross the exterior surface obliquely and converge near the crest. Striae commonly appear to represent the edges of thin (0.1-0.5 mm thick) sheets of lamellae which are imbricated in the direction in which the striae converge (when viewed in hyporelief). The burrow exhibits an inner core which consists of a smooth-walled rod (50-75% of burrow diameter) with a circular to almond-shaped transverse section. Where the outer sheath of lamellae was locally not preserved, the ichnofossil consists only of the smooth-walled rod.

Preservation. Toponomic - full relief, convex hyporelief.

Uchirites ascendens sp. nov.

Plate 15, figs. 1,3,4,7

Etymology. Latin 'ascendens', moving upwards; referring to the development of retrusive spreite during predominantly upward migration of the producer.

Material. Fifteen specimens from the Douro Formation of Somerset and Devon Islands. The holotype (GSC 64060) was collected from strata 36.3-40.4 m above the base of the Douro Formation from cliffs on the southwest side of Dealy Point, Devon Island (Text-fig. 19, locality H).

Diagnosis. Unbranched Uchirites exhibiting retrusive spreite.

Description. Burrows occur as straight to slightly curved, unbranched hypichnial ridges 4-11 (average 8.0) mm wide and up to 120 mm long. Ridges are subtriangular in transverse section; crests most commonly point downwards but rarely point horizontally. Burrows are covered with numerous fine striae which cross the exterior surface obliquely and converge near the crest of the ridge. In many specimens the striae are simple lines, but in several well-preserved specimens they appear to represent the edges of thin (0.1-0.2 mm thick) imbricated sheets of sediment; imbrication is in the direction in which the striae converge (when viewed in hyporelief). In transverse section, specimens

exhibit either a well-developed retrusive spreite or a wall of disturbed sediment with rare septa; this zone is up to 25 mm deep. The septa are most commonly parallel to stratification. In one specimen the septa are inclined, giving the ichnofossil an imbricated surface appearance; specimens with crests oriented horizontally exhibit horizontal retrusive spreite (septa perpendicular to stratification).

Preservation. Toponomic - full relief, convex hyporelief.

Uchirites ramosus sp. nov.

Plate 15, figs. 9,10,?fig. 8

v1970 'trail of unknown affinity'; Rodriguez and Gutschick, Pl. 10, fig. c

Etymology. Latin 'ramosus', full of branches.

Material. Fourteen specimens observed (8 collected) from the Douro Formation of Somerset, Cornwallis and Devon Islands, and the Cape Storm Formation of Cornwallis Island. The holotype (GSC 64052) was collected from strata 44.7-48.8 m above the base of the Douro Formation, along the side of an unnamed stream 3 km south of Two Rivers Bay, Somerset Island (Text-fig. 19, locality D).

Diagnosis. Uchirites exhibiting true branching.

Description. The gently curved, branched burrows occur as hypichnial ridges with triangular transverse sections. Crests of ridges may be directed either downward or laterally, even within a single specimen. The ridges are covered with numerous fine striae which cross the exterior surface obliquely and converge near the crest; striae commonly appear to represent the edges of thin (0.1-0.2 mm thick) sheets of lamellae which are imbricated in the direction in which the striae converge (when viewed in hyporelief).

Most specimens exhibit four to eight secondary tunnels which branch off the main shaft in an irregular to palmate pattern; the diameters of the main shaft and secondary tunnels are constant within any individual specimen, and range from 1.5 to 7 mm among the different specimens. Internal structure is generally poorly preserved, but one specimen (the holotype) exhibits a structureless, almond-shaped inner core surrounded by a sheath of lamellae. One individual questionably referred to U. ramosus (Pl. 15, fig. 8) exhibits sickle-shaped tunnels (2-4 mm in diameter) which branch off one side of a main shaft (6-8 mm in diameter), pass around it, and extend upwards into the overlying bed. A zone of disturbed sediment 15 mm deep immediately

overlies the proximal end of the burrow; the distal end exhibits structure typical of the holotype.

Preservation. Toponomic - convex hyporelief, full relief.

Comparisons. U. triangularis Macostay, 1967 (type species of Uchirites) and S. lenadumbratus Chamberlain, 1971a (type species of Sustergichnus) both comprise relatively small burrows covered with numerous fine striae which cross the exterior surface obliquely and converge near the crest of the ridge. Both are unbranched, and occur predominantly as hypichnial ridges with triangular transverse sections. There is no significant difference between them, and Sustergichnus Chamberlain is herein regarded as a subjective junior synonym of Uchirites Macostay, as originally suggested by Seilacher (1977b, p. 363).

Uchirites is broadly similar to a number of ichnogenera, notably Keckia Glocker, Muensteria von Sternberg, Olivellites Fenton and Fenton, Halymenidium Schimper and Gyrochorte Heer. Most of these ichnogenera are poorly understood (Häntzschel 1975; Książkiewicz 1977). However, it appears that none of them exhibits the diagnostic features of Uchirites, particularly an outer sheath with numerous fine striae arranged in a herringbone pattern. The striae on Keckia, Muensteria and Olivellites apparently represent surface expressions of septa

(Häntzschel 1975), the striae on Halymenidium are considerably more irregular and apparently represent marks of tubercules and spines (Książkiewicz 1977, p. 61), and the striae on most species of Gyrochorte are biserially-arranged, plaited ridges (Häntzschel 1975). One exception, G. burtani Książkiewicz 1977, is similar in size and overall morphology to Uchirites. Indeed, the holotype (Książkiewicz 1977, pl. 11, fig. 1) clearly exhibits a structureless inner core surrounded by a sheath covered with numerous fine striae arranged in a herringbone pattern, rather than the plaited ridges diagnostic of Gyrochorte. G. burtani does not exhibit a number of other features typical of Gyrochorte (Książkiewicz 1977, p. 114), and is herein regarded as a subjective junior synonym of Uchirites lenadumbratus (Chamberlain).

U. ramosus sp. nov. can be distinguished from all other species of Uchirites by the presence of true branching. It somewhat resembles the branched specimens of Crossopodia dichotoma Bandel, 1967, but the striae on C. dichotoma apparently represent curved segments (Bandel 1967, pp. 5-6) rather than a sheath of lamellae. The specimen of ?U. ramosus resembles the Cambrian ichnofossil Phycodes pedum Seilacher, 1955 in its pattern of branching, but exhibits the pattern of fine striae diagnostic of Uchirites.

U. lenadumbratus (Chamberlain) and U. ascendens sp. nov. can be distinguished only on the basis of internal structure. U. lenadumbratus exhibits a structureless inner core surrounded by a striated sheath, whereas U. ascendens exhibits spreite. Unfortunately, Macostav did not figure the internal structure of U. triangularis, and the present author was unable to obtain any type material. Until type material is sectioned, it will not be known whether U. triangularis is the senior synonym of U. lenadumbratus or U. ascendens, or represents a distinct species.

Remarks. The presence of retrusive spreite in U. ascendens and palmate branching in some specimens of U. ramosus suggest that Uchirites represents a feeding trace. The smooth-walled tube suggests a vermiform originator. The worm probably worked through the sediment, packing the reworked material in thin imbricated sheets. The pattern of branching in U. ramosus, and the direction of imbrication (when viewed in epirelief) indicate that movement was in the sense opposite to that in which the striae converge.

Uchirites has been recorded from shallow subtidal and flysch deposits (Chamberlain 1978a). U. ascendens and U. ramosus have been observed only in shallow subtidal shelf deposits.

CONCLUSIONS

1. Trace fossils can be valuable paleoenvironmental indicators in carbonates, particularly when used in conjunction with other paleontologic and sedimentologic indicators.
2. The original distribution of trace-making organisms is probably largely independent of substrate mineralogy.
3. Early and late diagenetic processes can significantly affect the preservation and diversity of trace fossil assemblages.
4. Characters resulting from formational and preservational processes of trace fossils can yield information on substrate consistency.
5. Trace fossils can provide paleontologic and paleoecologic information not readily available from body fossils. In the present study, the abundance of Skolithos, Arenicolites, Chondrites, Teichichnus, Bergaueria and other ichnogenera indicates that soft-bodied filter feeders, deposit feeders and predators were an important part of the ecosystem. Specimens of the trilobite trace fossils Monomorphichnus and Petalichnus suggest that their originators had two claws on each foot.

Plate 11

Trace fossils. All magnifications X 1, except fig. 4 X 1.5; figs. 5,8,9 X 2.

Fig. 1. Syncoprulus aff. pharmaceus (Richter and Richter), epirelief, 5-7 m below top Cape Storm Formation, locality F, GSC 64021.

Fig. 2. Bergaueria sp. Six specimens in hyporelief, scree from Leopold Formation, locality I, GSC 64024.

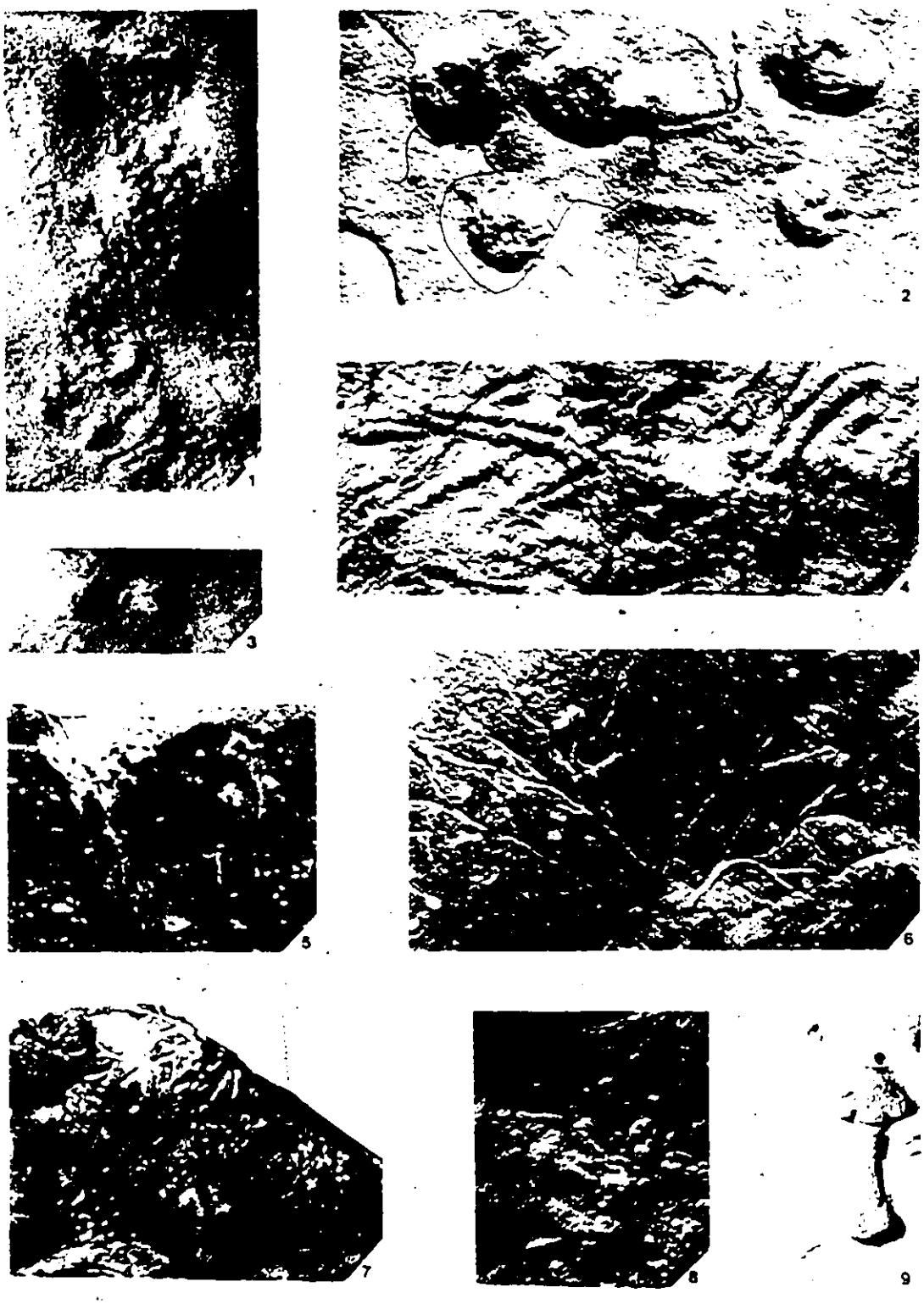
Figs. 3,5. Arenicolites carbonarius (Binney). 3, hyporelief, 39-40 m below top Cape Storm Formation, locality F, GSC 64022. 5, cross-section showing funnel-shaped aperture on left limb and poor preservation of right limb of tube, 41-43 m below top Douro Formation, locality A, GSC 64023.

Fig. 4. Cruziana problematica (Schindewolf). Hyporelief, band-like and connected buckle-like forms, 40-43 m below top Leopold Formation, locality D, GSC 64031.

Fig. 6. Chondrites - type 2. Epirelief, 15-19 m below top Cape Storm Formation, locality F, GSC 64028.

Fig. 7. Chondrites - type 1. Epirelief, four specimens intersected at different levels by a bedding surface, scree from uppermost 30 m Douro Formation, locality H, GSC 64027.

Figs. 8,9. Bifungites fezzanensis Desio. Hyporeliefs. 8, several specimens exhibiting a mixture of hemispherical and spherical terminations, approximately 25 m below top Leopold Formation, locality E, GSC 64025. 9, specimen exhibiting one hemispherical and one arrowhead-shaped termination, 17-19 m above base Douro Formation, locality D, GSC 64026.



Pl. 11

Plate 12

Trace fossils. All magnifications X 1.

Figs. 1,2,4,5. Fuersichnus douroensis sp. nov. 1, epirelief of oval specimen, scree from basal 30 m Douro Formation, locality C, GSC 64034. 2, cross-section exhibiting two stacked horizontal spreiten, 121-122 m above base Douro Formation, locality F, GSC 64036. 4, cross-section exhibiting a subhorizontal spreite, 35-38 m above base Douro Formation, locality D, GSC 64035. 5, holotype, hyporelief of crescentic specimen, 15-17 m above base Douro Formation, locality D, GSC 64033.

Fig. 3. Helicodromites mobilis Berger. Hyporelief, 36-40 m above base Douro Formation, locality H, GSC 64038.

Fig. 6. Helicodromites arctatus sp. nov. Holotype, hyporelief, 255-266 m above base Douro Formation, locality K, GSC 64039.

Fig. 7. Cochlichnus sp. Epirelief, 35-39 m above base Douro Formation, locality D, GSC 64029.

Fig. 8. Diplocraterion sp. Hyporelief 27-28 m above base Douro Formation, locality D, GSC 64032.

Fig. 9. Gordia sp. Hyporelief, 31-33 m below top Leopold Formation, locality D, GSC 64037.

Fig. 10. Uchirites lenadumbratus (Chamberlain). Hyporelief, transition from smooth walled tube (inner core) to bilobate striated ridge (outer sheath) from upper left to lower right, 27-33 m above base Douro Formation, locality H, GSC 64065.

Pl. 12

Plate 13

Trace fossils. All magnifications X 1, except figs. 1,2,5 X 0.5.

Fig. 1. Laminites kaitiensis Ghent and Henderson. Epirelief, 68-74 m below top Cape Storm Formation, locality F, field photograph, GSC 64030.

Fig. 2. ?Laminites sp. Hyporelief, 0-2 m below top Leopold Formation, locality D, field photograph, GSC 64042.

Figs. 3,6. Phycodes palmatum (Hall). Hyporeliefs. 3, specimen exhibiting irregular palmate branching, 36-40 m above base Douro Formation, locality H, GSC 64050. 6, two specimens from basin slope facies exhibiting regular palmate branching, 125-155 m below top of tongue of (?)Cape Phillips Formation, locality F, GSC 64051.

Fig. 4. Margaritichnus? sp. Hyporelief, 125-155 m below top of tongue of (?)Cape Phillips Formation, locality F, GSC 64040.

Fig. 5. Laevicyclus sp. Epirelief, 61 m above base Douro Formation, locality D, GSC 64041.

Pl. 13

Plate 14

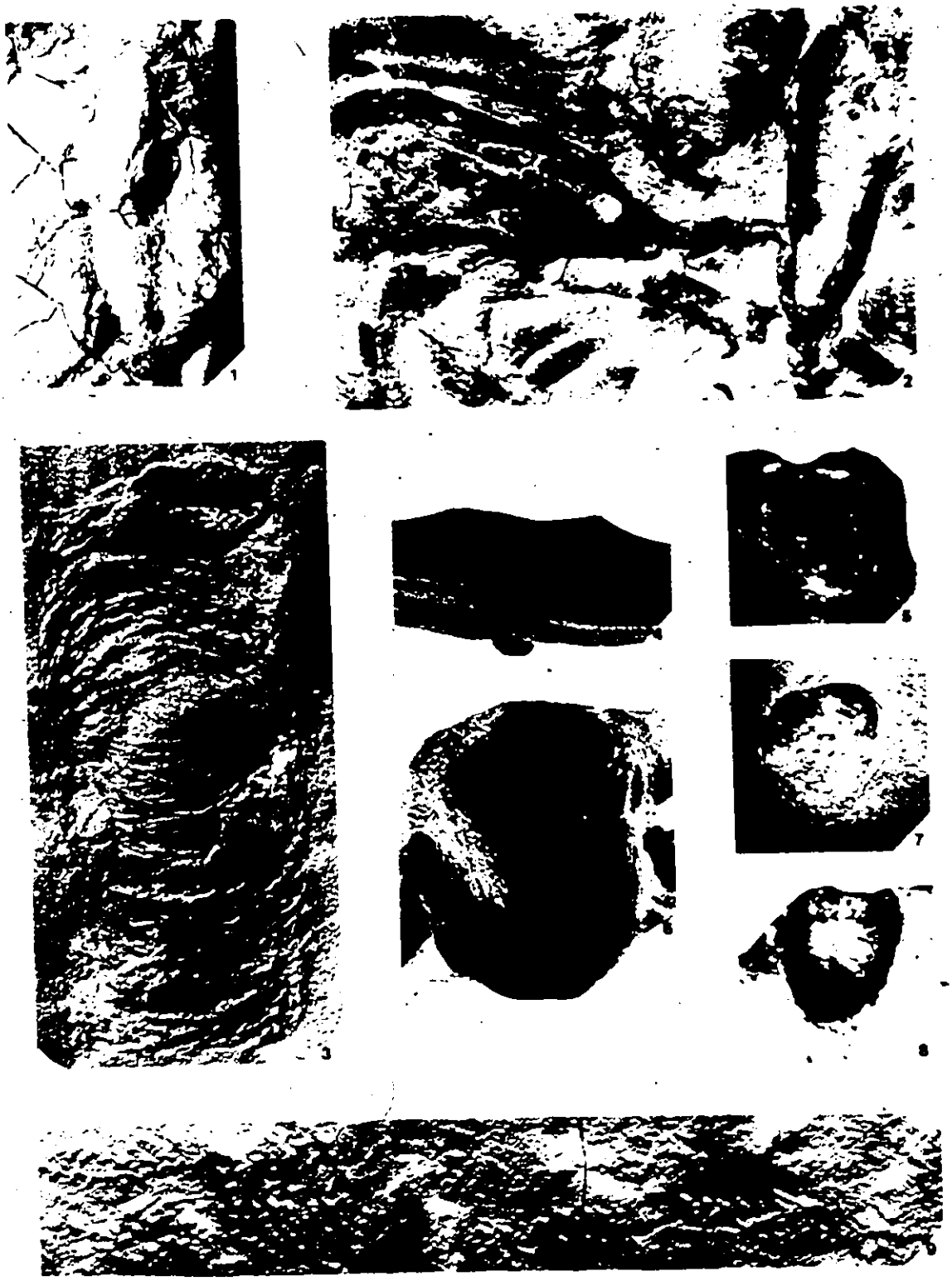
Trace fossils. All magnifications X 1, except figs. 4,6 X 2; fig. 5 X 6; figs. 7,8 X 4.

Figs. 1,2,5,7,8. Palaeophycus sp. 1, hyporelief, smooth-walled tube visible where micro-faulted silt layer has flaked off (near centre), 18-19 m above base Douro Formation, locality B, GSC 64045. 2, epi-relief, note ridge of sparite along crest, 102 m below top Douro Formation, locality A, GSC 64044. 5, negative print of cross-section showing calcilutite fill except for a thin channel of sparite at crest of burrow, 142-145 m below top Douro Formation, locality A, GSC 64046. 7, cross-section showing geopetal calcilutite/sparite fill, microtectonic fractures above and to right of tube, 93-94 m above base Douro Formation, locality D, GSC 64047. 8, cross-section showing sparite fill, 170-172 m below top Douro Formation, locality A, GSC 64048.

Fig. 3. Polarichnus garnierensis Narbonne. Hyporelief exhibiting rectangular shape and spreite with major and minor lamellae, scree from uppermost 10 m Leopold Formation, locality D, GSC 64054.

Figs. 4,6. Teichichnus rectus Seilacher. Cross-sections. 4, small variety, 45-59 m above base Douro Formation, locality D, GSC 64059. 6, large variety, 11-12 m above base Douro Formation, locality B, GSC 64058.

Fig. 9. Petalichnus sp. Hyporelief, movement from left to right, 39-40 m below top Cape Storm Formation, locality F, GSC 64049.



Pl. 14

Plate 15

Trace fossils. All magnifications X 1, except figs. 4,7 X 3.

Figs. 1,3,4,7. Uchirites ascendens sp. nov. 1, holotype (curved specimen), hyporelief of two crossing specimens, 36-40 above base Douro Formation, locality H, GSC 64060. 3, hyporelief, crest directed laterally on the bedding plane, 45-49 m above base Douro Formation, locality D, GSC 64062. 4, holotype, cross-section showing retrusive spreite. 7, cross-section showing zone of disturbed sediment with rare septa, 27-33 m above base Douro Formation, locality H, GSC 64061.

Fig. 2. Uchirites lenadumbratus (Chamberlain). Hyporelief, 15-17 m above base Douro Formation, locality D, GSC 64063.

Fig. 5. Skolithos verticalis (Hall). Cross-section, stained with Alizarin Red-S, note protrusive Teichichnus to left, 124-125 m below top of tongue of (?)Cape Phillips Formation, locality F, GSC 64057.

Fig. 6. Scalarituba missouriensis Weller. Hyporelief of two specimens, 125-155 m below top of tongue of (?)Cape Phillips Formation, locality F, GSC 64056.

Fig. 8. ?Uchirites ramosus sp. nov. Hyporelief, 40-43 m above base Douro Formation, locality H, GSC 64053.

Figs. 9,10. Uchirites ramosus sp. nov. Hyporeliefs. 9, 5-8 m below top Cape Storm Formation, locality F, GSC 64064. 10, holotype, 45-49 m above base Douro Formation, locality D, GSC 64052.

Fig. 11. Rusophycus pudicum Hall. Hyporelief, 56-60 m above base Douro Formation, locality D, GSC 64055.

Fig. 12. Monomorphichnus bilinearis Crimes. Hyporelief of two specimens, prod marks oriented north-south, 60 m above base Douro Formation, locality D, GSC 64043.

Pl. 15

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